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FIRE SAFETY JOURNAL

Fire Safety Journal has become established as the leading publication which deals with all aspects of fire safety engineering. Its scope is purposefully wide, as it deemed it to be important to encourage papers from all sources within this multidisciplinary subject, thus providing a forum for its further development as a distinct engineering discipline. This is an essential step towards gaining a status equal to that enjoyed by the other engineering disciplines.

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- People/fire interactions (physical, physiological and psychological)
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- Assessment and quantification of fire risk (including acceptability of risk)
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- Fire safety design (including consumer items, industrial plant, transportation, buildings, etc.)
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Original contributions relating to any of the above topics are invited, particularly if they incorporate a quantitative approach to the subject in question.

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Smoke and Heat Release and Ignitability as Measures of Fire Hazard from Burning of Carpet Tiles*

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ABSTRACT

A series of 22 *commercial carpet tiles, covering the range of backings found in the marketplace, and with the same face material (nylon) was chosen for fire testing. All the carpets were tested in the cone calorimeter rate of heat release apparatus. They were also all tested in the NBS smoke density chamber, in the flaming mode. A selection of samples was further tested using the flooring radiant panel. A preliminary investigation was made to choose the optimum radiant incident flux to be used, which was determined to be* 25 kW/m^2.

It was found that the carpets showed a wide range of fire performance, including ranges of peak rate of heat release and of time to ignition of c. 3 *and of smoke factor of* c. 8. *It was not found possible to correlate the results of the NBS smoke chamber or radiant panel tests with any of the results obtained from the cone calorimeter. A classification scheme was proposed to determine fire performance of carpets, based on the ratio of time to ignition (in seconds) and peak rate of heat release (in* kW/m^2*). According to this scheme, four categories of fire performance would be expected:*

I		*Ratio*	≥0·40
II	0·40>	*Ratio*	≥0·20
III	0·20>	*Ratio*	≥0·10
IV	0·10>	*Ratio*	

* A version of this paper was presented at the International Conference on Fires in Buildings, in Toronto, Canada, in September 1989.

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In specific applications, where smoke obscuration is considered an issue, carpets with low values of smoke factor can offer an improvement within a category. None of the carpets tested were found to fall in the lowest fire performance category (IV), but they covered the whole range of the other categories.

INTRODUCTION

Once ignition has taken place, fire involves a series of three processes; (1) generation of fire products (heat, smoke and toxic products); (2) transport of the fire products from the source to the target; and (3) effects of the fire products on the target.[1]

Fire hazard can be defined as the potential for causing harm to people, property or operations as the result of a fire. As far as fire hazard to humans is concerned, the main issues to be addressed are:

—Heat effects
—Lack of visibility
—Toxicity of smoke
—Transport of smoke
—Decay of smoke components

The first three issues are functions of space and time. Therefore, if the fire involves sufficient products so as to progress beyond the room of origin, it is necessary to address the effects on people remote from the room of origin. In that case, the two final issues are additional aspects that need to be considered.

There are thus three ways in which fire, irrespective of the products involved, can lead to harm to people, property or operations. These are, in decreasing order of their importance to fire hazard: (a) effects of heat or flames spreading from the item first ignited to other products, potentially resulting in thermal injury to people, destruction of property or loss of operation; (b) production of smoke which obscures vision and possibly hinders both the escape of trapped victims and the action of fire fighters; and (c) generation of toxic products (gases and particulates) in smoke which can be inhaled by victims and injure them. The reason for stating that there is a hierarchy between these ways is because it is the heat from the fire that causes the generation of combustion products (i.e. smoke) and the smoke which is toxic. Thus, in the absence of heat there will be no smoke and in the absence of smoke there are no toxic products.

It should be clarified here that toxicity of smoke refers to the toxicity of the smoke present in the fire environment rather than to the toxic

potency of the smoke generated by an individual product burning, as measured in a specific small-scale test.

Thus, fire hazard is associated with the combination of a large number of fire properties, including ignitability, flame spread, ease of extinction, amounts and rates of release of heat (RHR), smoke and toxic gases. It has now become clear that the single property which most clearly defines the magnitude of a fire is its peak RHR.[2,3] In fact, the importance of heat release rate as *the* measure of fire hazard vastly exceeds those of ignitability, flame spread or toxicity [e.g. Ref. 4]. The heat release rate governs not only the burning rate (and mass loss rate) of the product being consumed, but also the amounts of other products (present in the fire compartment or in other compartments) which will be ignited and burn. The RHR also governs, therefore, the overall amount of smoke and combustion products being generated in a full-scale fire, since any other products present will be ignited only if sufficient heat reaches them rapidly.

In the final analysis, the issue of interest is the hazard in a real fire. Much research has been done to identify the relationship between the properties of materials as measured in small-scale tests and the performance of products made from them under real fire conditions.[5,6] In the early stages of fire testing, it was thought that small-scale tests must be designed so that they represent 'sized down' versions of the product to be tested. Recent understanding of fire phenomena has shown that the important issue is to have the correct test design to measure fundamental properties and to take into account heat effects. The best approach to assess fire hazard is, probably, to estimate the rate of growth of a real fire (or perhaps the time available before flashover) based on measuring, in a small-scale test, the peak RHR for those materials used to manufacture the burning product. The rate of burning can be expressed in terms of the rate of mass loss. Yield factors can be measured in small-scale tests to give the amounts of heat, smoke and toxic gases generated per unit mass burnt.[6] They can then be coupled with the burning rate of the real fire to estimate the potential buildup of heat, smoke and toxic gases in the real fire.[4] It needs to be pointed out that some fire properties can only be measured inadequately in small-scale tests, particularly smoke obscuration and carbon monoxide yields. Smoke obscuration, as measured in small-scale tests, requires a correction to account for the amount of material burning before extrapolation to full-scale tests.[7] Carbon monoxide yields are usually underestimated in small-scale tests.[8] Rate of heat release can be measured in instruments called rate of heat release (or RHR) calorimeters.[6,9–11]

Recently, the US National Bureau of Standards (now called the National Institute for Standards and Technology) developed the latest such RHR calorimeter, the NBS cone calorimeter rate of heat release apparatus.[11] Data from the cone calorimeter can be used in fire models to evaluate the predicted course of development of a potential fire. It has also been repeatedly shown that the data measured in this instrument correlate well with those found in full-scale fires (e.g. Refs 7).

Traditional determinations of RHR have been made by calorimetric procedures wherein perfectly adiabatic chambers are assumed. This requires all heat losses to be minimal, if not zero—an almost impossible task. Alternatively, the heat losses must be identical during calibration and tests, also a difficult task. The RHR is measured in the cone calorimeter by taking advantage of the principle that, for a wide variety of fuels, a fixed amount of oxygen is consumed for every unit of energy (heat) which is released by the combustion process.[12] This means that heat losses are of no importance, as long as all the combustion gases are captured into the hood, a task which is relatively simple to achieve.

The relationship between the peak RHR measured in the cone calorimeter for a small representative sample of an article and the peak RHR of the whole article under realistic burning conditions has been investigated for many products, including furniture items.[13] Good correlations were found. The peak RHR, as measured in laboratory RHR calorimeters, can also be used for estimating the flame spread rate of cables in large-scale tests.[14–16] Overall, the peak RHR of a product is highly significant because it is directly related to how large a fire will become. This, in turn, directly controls how high the temperature will get, how far the fire will spread to damage surrounding areas and how much smoke and toxic gases will be generated. Such results, from the cone calorimeter, have often been correlated with those from large-scale fires (e.g. Refs 17–18).

Before carrying out fire hazard assessments for an individual product, special considerations need to be made regarding its intended use. Two considerations are peculiar to floor and ceiling coverings (although it should be remembered that the same products may sometimes be used for other applications, and these uses would require different fire hazard assessments):

(1) They are almost always used in a horizontal orientation.
(2) Horizontal flame spread in the x and y directions are of equal importance, as far as the product is concerned.

Additionally, floor coverings are very distinctive products in that the

heat released in any fire tends to be directed upwards, and thus away from the product being assessed, i.e. the floor covering.

There are three tests which have been especially developed to measure fire performance of floor coverings: ASTM E648 (flooring radiant panel test, measuring a critical radiant flux); ASTM D2859 (or its British version BS 6307, methenamine tablet test); and a similar test BS 4790 (using a hot steel nut as ignition source, i.e. with higher mass and representing smouldering). Many other tests are, of course, also relevant, particularly if the sample is exposed in the horizontal orientation.

In particular, two tests are of special interest: the NBS smoke density chamber (ASTM E662) and the cone calorimeter (ASTM E1354). The reason for choosing the first test is that it is often used for regulation or specification of carpets. However, the test is always run in the vertical orientation, which is of dubious relevance to floor coverings. Moreover, it has been extensively criticised [e.g. Ref. 19], particularly for yielding results which do not correlate with full-scale results. The cone calorimeter is the fire test with results best correlatable with full-scale fire test results [e.g. Ref. 16].

There are a whole variety of floor coverings and it was outside the scope of the present study to attempt to cover all of them. However, it was desired to make an investigation representative of the overall market, without special reference to individual materials or manufacturers. It was decided, therefore, to concentrate on carpet tiles, where one type of face (nylon fabric) has the overwhelming share of the market, although polypropylene, acrylic, wool and wool blends have some penetration. All samples used had a nylon face.

The present study has the following objectives:

(I) Find out the most appropriate incident flux for fire testing of carpet tiles in the cone calorimeter.

(II) Carry out fire tests on a wide variety of carpet tiles representing most of the typical constructions available.

(III) Compare the results of the fire tests carried out using the cone calorimeter with those using the NBS smoke density chamber and the flooring radiant panel tests.

EXPERIMENTAL

Materials

A total of 22 carpet tiles were tested. The carpet tiles used were commercial products, all of them with a nylon face, produced by

various manufacturers. They had a variety of constructions and backings and represent a valid cross-section of the carpet tiles available on the marketplace. They will be identified here simply by numbers, so as to avoid any diffusion of the main focus of this paper. For comparison purposes, some testing was also done with standard poly(methyl methacrylate) (PMMA, Polycast Bk 2025, 6 mm (0·25 in) thick).

Apparatus and procedure

The NBS cone calorimeter

A detailed description of the cone calorimeter is given in ASTM E1354 'Test method for heat and visible smoke release rates for materials and products using an oxygen consumption calorimeter', first published in 1990. Further details are given in an NBS Users' Guide.[20]

The cone calorimeter used in this work was manufactured by Custom Scientific Instruments, Inc., Cedar Knolls, New Jersey (CSI no. CS237). It includes systems for continuous measurement of oxygen consumption, smoke obscuration, and sample mass during burning, as well as gravimetric determination of soot formation in each experiment, and sampling sites for measurements of other toxic gases. The sample to be burnt is placed on a weighing cell, underneath a conically shaped heater unit, of adjustable intensity. A continuously operated electrical spark is the ignition source, to initiate flaming combustion of the sample. Combustion products are drawn into an air flow stream of controlled flow rate. Smoke obscuration measurements are made using a laser beam source/light intensity detector system, which views across the air stream containing the smoke. A small fraction of the air flow stream is also taken for gravimetric determination of soot fraction, and another one was also taken for continuous measurements of concentrations of toxic gases, in some cases. Gas concentrations were measured as follows: carbon monoxide (CO), carbon dioxide (CO_2) and water (H_2O), with Beckman 865 non-dispersive infrared analysers, hydrocarbons (CH_x) with a Beckman 402 flame ionisation detector analyser, nitrogen oxides (NO_x) with an Aerochem AA chemiluminescence detector and hydrogen chloride (HCl) with a Thermo Electron 15 gas filter correlation analyser. Testing was carried out at incident fluxes of 20, 25, 30 and 40 kW/m^2. All samples (standard 4 in × 4 in pieces, i.e. 10 cm × 10 cm) were tested in the horizontal orientation, and at use thickness. Experiments were normally carried out in duplicate.

The other fire tests used were:

(a) Maximum smoke density, in the flaming mode (D_m(F)), by means of an NBS smoke density chamber (500 litres) designed to meet ASTM E662 test requirements, with sample size of 76·2 mm × 76·2 mm × 1·0 mm (3 in × 3 in × 0·04 in), at 25 kW/m^2 incident radiant flux, in the vertical orientation.
(b) Critical radiant flux, by means of a flooring radiant panel, designed to meet ASTM E648 test requirements, with sample size of 1 m × 0·2 m.

Both of these tests can be used to determine other parameters. It is possible to burn samples in the NBS smoke chamber in the non-flaming mode. Smoke obscuration in the duct and rate of flame spread can be obtained from the flooring radiant panel. However, the data presented here are the most widely used ones.

Description of cone calorimeter parameters and their significance

Cone calorimeter: parameters reported

The parameters reported from the cone calorimeter tests are: peak rate of heat release (Pk RHR, kW/m^2), the time to sustained combustion, or time to ignition (TTI, s), the total heat released (THR, MJ/m^2), the smoke factor (SmkFct, MW/m^2), the mass loss rate parameter (MLRP, g/m^2 s^2), the heat of combustion (Ht Comb, MJ/kg), the average extinction area (Av Ext Ar, m^2/kg), the mass loss rate (MLR, g/s) and the percentage of mass loss (Ms Loss, %). Some of these variables may not be generally known and will therefore be explained briefly.

Rate of heat release

The RHR is a measure of the instantaneous amount of heat being released per nominal sample surface area. For each experiment, the maximum RHR value was felt to be the most significant one and is recorded here in the tables. The RHR values are calculated from the differences between the values of oxygen concentration measured and the background oxygen in the atmosphere. In general, the RHR–time curve passes through a maximum shortly after sample ignition. As the available fuel is consumed, the RHR declines. Then, as deeper layers are exposed, additional maximum values of RHR may occur. In particular, a composite system such as a carpet is likely to present at least two maxima, one for the face and one for the backing.

Total heat released
The THR in each experiment per unit nominal sample surface area is determined by integrating the RHR data as a function of time.

Time to ignition
The time to ignition is the time expressed in seconds, for the entire surface of the sample to burn with a sustained luminous flame.

Heat of combustion
This is the effective amount of heat released by the material, per unit mass burnt, in MJ/kg.

Average specific extinction area
The average specific extinction area is an expression of the instantaneous amount of 'smoke' being produced by the sample per unit mass of sample burnt. Smoke in this context refers to those components of the combustion product mixture responsible for smoke obscuration, i.e. for decreasing the amount of light transmitted. Results are expressed in units of m^2/kg. This is the original way of expressing smoke obscuration results for the cone calorimeter, and it is unique to instruments that can continuously measure sample mass together with fraction of light transmitted. The average specific extinction area results may be used as input data in some fire models to estimate the smoke obscuration performance of products in large-scale fire tests. Full-scale and small-scale results have been shown to correlate well only for products which burn up completely in the large scale test.

Rate of smoke release
The RSR is an expression of the instantaneous amount of 'smoke' being released by the sample as it burns in the cone calorimeter, per nominal sample surface area. Smoke in this context again refers only to those components of the combustion product mixture responsible for smoke obscuration, i.e. for decreasing the amount of light transmitted. Results are expressed in units of $1/(s\ m^2)$. RSR results are useful for comparing the performance of materials in the cone calorimeter with those in other RHR calorimeters where mass loss cannot be measured during the burning process. The specific extinction area is related to RSR by the ratio of the mass loss rate and the sample area. Thus, the rate of smoke released is a more direct measurement property (volumetric flow rate times optical density (corrected for decimal logarithms) divided by sample area times light path length) than the specific extinction area.

Total smoke released

The TSR is the equivalent of the THR, for the property of smoke obscuration, again per unit of nominal sample surface area and corresponds to full sample destruction. Total smoke released is, thus, unlikely to represent most real fire scenarios, where samples are not normally totally destroyed. It is determined as the time integral of the RSR data. Its units are $1/m^2$.

Smoke factor

The smoke factor is a smoke/fire hazard variable used to estimate the potential amount of smoke that a product would generate under full-scale fire conditions.[7,21–23] It is a realistic approach for such an estimate which takes into account both the potential for smoke obscuration for full sample destruction and the potential to cause other products to burn and release smoke in a real fire. It does so by incorporating the burning rate (as the peak rate of heat release). This takes into account the fact that those products made from materials with low peak RHR are less likely to burn up totally in a fire, and will, furthermore, cause less smoke to be generated from the ignition of other products. It is calculated as the product of the total smoke released and the peak rate of heat release.[24] The single value presented here is that at 5 min. This has been shown to be a good estimation of full scale smoke for electric cables.[16]

Mass loss

This is the percentage mass lost during the burn tests (in % units).

Mass loss rate

Data from the sample weighing cell are used to calculate continuously the rate of sample mass loss. The results are expressed in units of g/s. The MLR (or rate of generation of combustibles) gives an indication of overall toxic hazard in a fire, since the toxic potency of most materials is similar.

Mass loss rate parameter

The MLRP is a single quantity, measured to give a quick and rough indication, together with the toxic potency, of the potential toxic hazard. The MLRP is the ratio of 80% of the overall mass loss to the time period between 10 and 90% mass loss and the time to ignition (expressed in units of g/s^2).[25]

Average yields of combustion gases

The average yield of a combustion gas is an expression of the mass of the gas produced per unit mass of material burnt. It is a non-dimensional quantity, expressed as the ratio of the mass formed of a particular gas to the mass of product burnt. They could also be used to assess the potential toxic hazard by estimating the concentrations of each individual toxic gas formed by a burning product under full-scale fire test conditions. However, they tend to be of much less importance than the average mass loss rate in determining fire hazard, since this test, as all small-scale tests, underestimates the yield of carbon monoxide, which is the principal toxicant in fires. Some recent findings give particular validity to this statement. First, it has been found (i) that over 90% of all fire victims have blood carboxyhemoglobin levels of over 20%, and that this level can be fatal, although it is not necessarily so, and (ii) that the carboxyhemoglobin distributions found in fire fatalities are very similar to those in deaths by CO poisoning.[26] Secondly, it has been found that CO levels in full-scale fires do not correlate with those in small-scale tests and are much more strongly dependent on the fire scenario and the flow dynamics in the room than on the materials involved in a fire.[8] The concentrations of other gases do correlate between small-scale cone calorimeter tests and full-scale tests. This indicates, once more, that carbon monoxide is the main toxicant in fire atmospheres, and that the best means of predicting toxicity of real fires is by average mass loss rate values. Measurements of yields of gases such as HCN, NO_x and HCl can, thus, give indications of levels to be expected, although their concentrations in real fires will be affected by smoke entrainment, transport and decay processes. Average gas yield values are reported for CO, CO_2, water, NO_x, HCl and hydrocarbons for the two initial tests carpets only.

RESULTS AND DISCUSSION

The first step in this investigation was to pick two carpet tile samples (no. 11 and no. 22), of similar construction and composition but where the backing of one was a superior product to the backing of the other. Rate of heat release tests were carried out on these carpets at a series of incident radiant fluxes: 20, 25, 30 and 40 kW/m^2. This was done in order to choose the most appropriate single flux for cone calorimeter testing of all subsequent carpet tile samples. The incident fluxes chosen are relatively low, in view of the known fact that the flux on to floor surfaces is generally lower than that on to walls or ceiling. Recent

work[27] showed that fluxes of up to 80 kW/m^2 can be obtained on carpets in rooms and values of 20 kW/m^2 in corridors, although room flux values are generally much lower unless there is a flashover scenario.

The average results for the runs on carpet tiles no. 11 and no. 22 are shown in Table 1. In Figs 1 and 2, comparisons are shown of the RHR versus time curves for a pair of runs carried out with each carpet tile at 20, 25, and 30 kW/m^2. The figures give a good indication of the reasonably good reproducibility found with this instrument. However, when a carpet tile sample shows some degree of fire retardance, its response to a low flux, such as 20 kW/m^2, can be somewhat erratic, because this flux may lie close to the threshold of ignitability of the sample. This effect can be seen on most properties and Fig. 1 exemplifies the behaviour for RHR. As the incident flux becomes higher, the variability in response becomes lower, but the fire performance of the samples also becomes less distinguishable. Therefore, the single most adequate incident flux must be chosen so that it is relevant and appropriate for the fire scenario to be considered. However, within that restraint, in order to classify fire performance of carpet tiles adequately a compromise is necessary between test reproducibility and sample distinguishability.

TABLE 1
Cone Calorimeter Fire Testing of Carpet Tiles

Carpet tile no.:	*11*	*22*	*11*	*22*	*11*	*22*	*11*	*22*
Input flux (kW/m^2):	*20*	*20*	*25*	*25*	*30*	*30*	*40*	*40*
Max RHR (kW/m^2)	340·5	640·7	502·4	684·0	601·3	692·3	594·4	652·9
TTI (s)	171	155	95	114	87	96	48	57
SmkFct (MW/m^2)	211	1 024	762	1 375	879	1 694	1 058	1 796
THR @ 15 min (MJ/m^2)	68·3	77·7	70·9	81·1	74·4	80·6	70·9	85·5
MLR @ 5 min (g/s)	0·097	0·095	0·054	0·074	0·058	0·045	0·013	0·038
Ht Comb (MJ/kg)	22·4	23·2	22·9	22·8	26·0	23·4	23·2	25·6
MLRP (g/m^{2}s^2)	0·9	1·1	1·4	1·3	1·6	1·7	2·0	NMSD[a]
Av Ext Ar (m^2/kg)	579	798	596	759	543	788	599	NMSD
Ms Loss (%)	65	70	67	72	67	72	63	NMSD
Max MLR (g/s)	0·142	0·241	0·180	0·257	0·199	0·253	0·200	0·300
Total heat (MJ/m^2)	68·3	77·9	70·9	81·6	74·3	81·2	70·9	85·6
CO avg (g/g)	0·068	0·078	0·055	0·084	0·077	0·083	0·067	0·022
CO_2 avg (g/g)	1·57	1·53	1·19	1·57	1·65	1·63	1·45	0·39
H_2O avg (g/g)	0·65	0·43	0·38	0·68	0·67	0·82	0·45	0·13
CH_x avg (g/g)	0·010	0·020	0·008	0·022	0·015	0·022	0·015	0·008
HCl avg (g/g)	0·325	0·139	0·083	0·140	0·119	0·141	0·103	0·033
NO_x avg (g/g)	0·004	0·003	0·001	0·002	0·001	0·002	0·003	0·001

[a] NMSD; not measured.

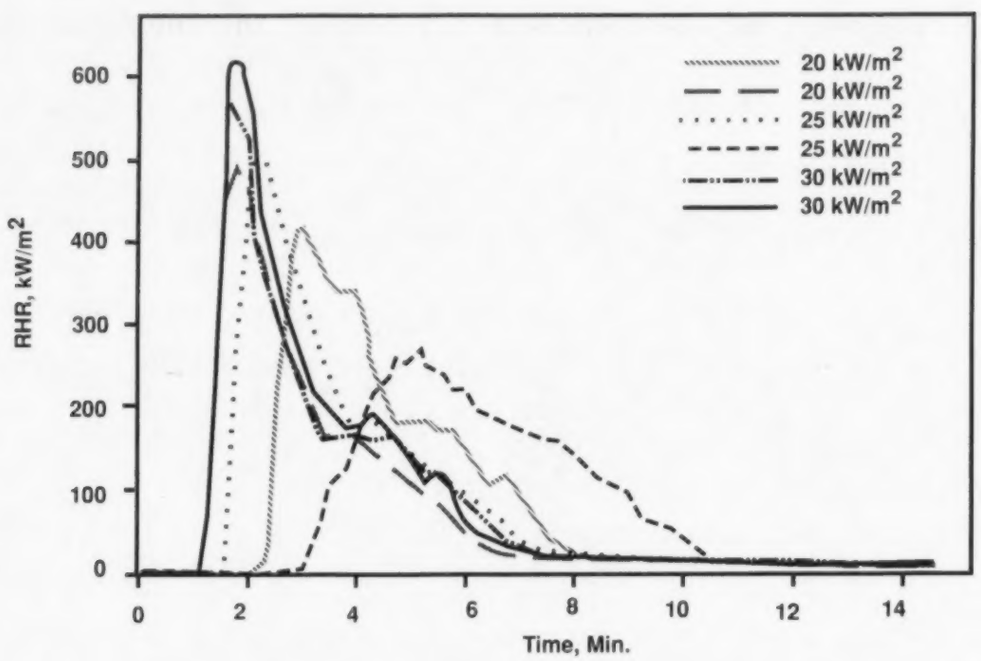

Fig. 1. Rate of heat release versus time for carpet tile no. 11, at various fluxes.

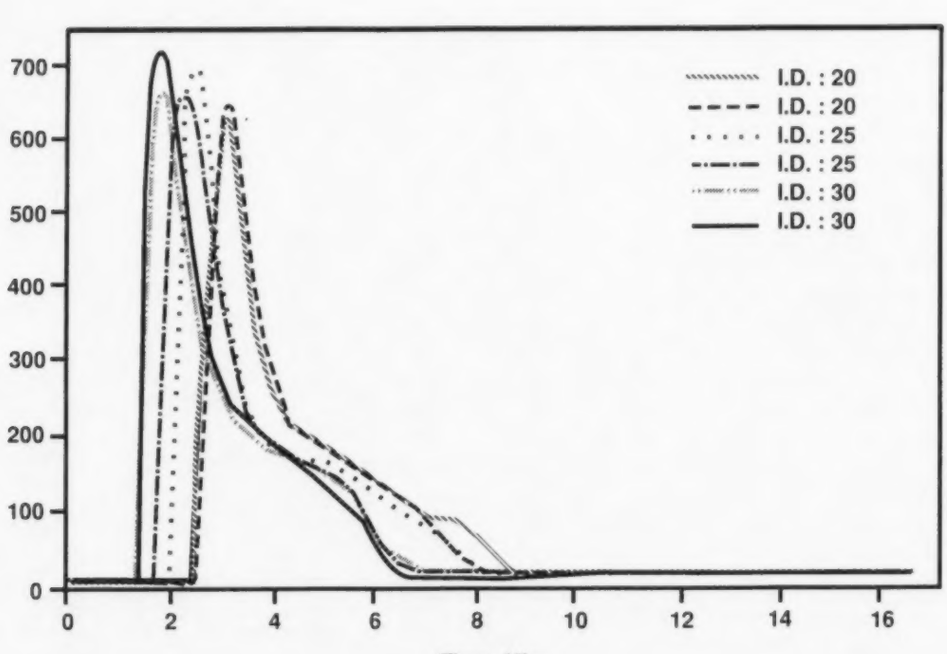

Fig. 2. Rate of heat release versus time for carpet tile no. 22, at various fluxes.

On comparing the two carpets, as per Table 1, the differences are:

Flux (kW/m^2)	25	30	40
TTI (s)	19	9	9
Pk RHR (kW/m^2)	182	91	58
THR (MJ/m^2)	similar at all three fluxes		
SmkFct (MW/m^2)	similar at all three fluxes		

These results suggest that 25 kW/m^2 (since the flux of 20 kW/m^2 was rejected for excessive irreproducibility) is the most logical incident flux to be used in the cone calorimeter in order to distinguish between the fire performance of various carpet tiles in the most efficient way. This flux is a realistic one for such products.[27]

The results in Table 1 suggest that the levels of toxic gases produced are of relatively low interest because they are within the expected normal ranges.

Table 2 is a compilation of the major results on all 22 carpet tiles at

TABLE 2
Cone Calorimeter Results, from All Samples, at 25 kW/m^2[a]

Carpet tile no.	*Pk RHR (kW/m^2)*	*TTI (s)*	*SmkFct 5 min (MW/m^2)*	*THR 15 min*	*MLRP ($g/m^2 s^2$)*	*Ht Cmb (MJ/kg)*	*Av Ext Ar (m^2/kg)*	*MLR 5 min (g/s)*	*MS Loss (%)*
1	222	153	231	43	1·3	14·5	639	0·106	79
2	315	159	207	56	1·5	18·7	453	0·110	54
3	358	142	474	56	1·0	22·9	735	0·068	57
4	359	131	500	70	1·9	17·2	872	0·121	83
5	368	171	323	60	0·9	25·7	636	0·062	46
6	393	167	240	92	1·0	30·5	593	0·082	77
7	396	72	1 003	55	2·9	15·1	755	0·062	78
8	441	140	198	66	1·1	23·8	259	0·068	59
9	470	186	289	74	0·9	28·8	486	0·086	49
10	487	110	518	60	1·7	19·4	470	0·058	69
11	502	95	762	71	1·4	22·9	596	0·054	67
12	521	90	1 061	48	1·9	18·0	763	0·021	57
13	531	90	748	65	1·8	21·6	510	0·044	65
14	531	84	801	52	1·1	25·0	825	0·004	73
15	544	119	574	78	1·0	32·2	578	0·062	61
16	547	83	248	72	1·2	31·1	257	0·009	69
17	557	69	1 099	81	1·3	39·8	1 005	0·009	49
18	573	86	842	72	2·4	20·0	599	0·070	65
19	601	84	1 180	70	1·5	22·8	809	0·055	66
20	635	101	1 630	65	1·4	21·3	925	0·027	64
21	648	212	698	73	1·0	24·3	708	0·072	73
22	684	114	1 375	81	1·4	22·8	759	0·074	72
PMMA	450	54	156	345	19·8	23·2	97	0·171	100

[a] In order of increasing Pk RHR.

25 kW/m^2 incident flux, organised in order of increasing peak RHR. The data for PMMA plaques are also included as reference. The ranges of fire performance in all fire properties are broad enough that it is perfectly possible to set up a variety of categories of carpet tile fire performance. In particular, the ranges of properties can be seen as follows:

Property	*Top of range*	*Bottom of range*	*Ratio*
Pk RHR	684	222	3·1
TTI	212	69	3·1
SmkFct	1 630	198	8·2
THR @ 15 min	92	43	2·1
MLRP	2·9	0·9	3·2
Ht Comb	39·8	14·5	2·7
Av Ext Ar	1 005	257	3·9

Unfortunately, a classification system based on any individual property will be different depending on the property chosen (see Figs 3 and 4). Thus, for example, carpet no. 21 has the highest, i.e. the best, time to ignition, but the second highest, i.e. the second worst, peak rate of heat release. Thus, it is likely that any classification scheme should be based on a combination of various properties.

However, it is worth remembering that the peak intensity of a fire is

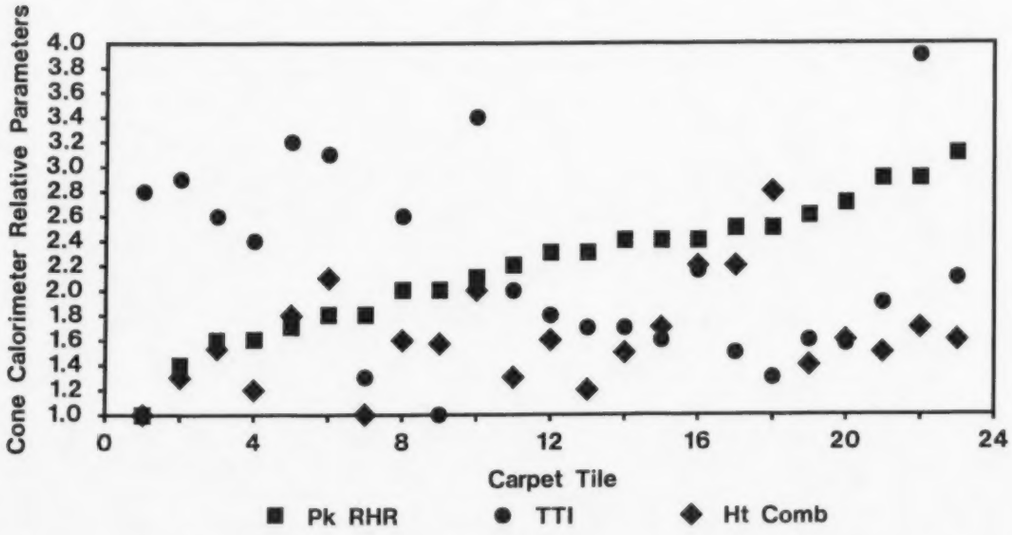

Fig. 3. Range of values found from testing all carpet tiles in the cone calorimeter at 25 kW/m^2, in relative numbers, with the basis of the carpet tile with lowest peak RHR. Values plotted: peak rate of heat release (Pk RHR), time to ignition (TTI) and heat of combustion (Ht Comb).

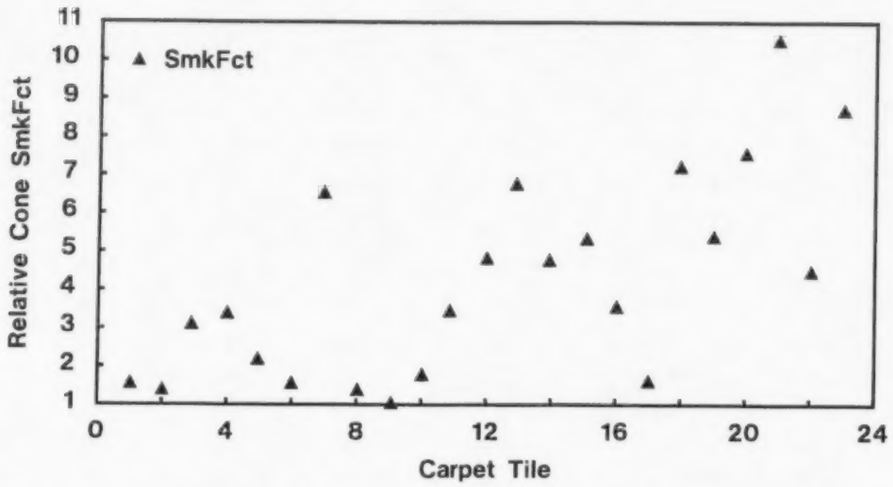

Fig. 4. Range of values found from testing all carpet tiles in the cone calorimeter at 25 kW/m^2, in relative numbers, with the basis of the carpet tile with lowest peak RHR. Values plotted: smoke factor (SmkFct).

proportional to the peak RHR. Thus, the single most meaningful property is likely to be that same peak RHR. On the other hand, if the intention is to minimise the flame spread rate, it is important to recognise that it has been shown that the inverse of the time to ignition is proportional to the flame spread rate.[13] It may, thus, be most useful to investigate a parameter such as the ratio of the time to ignition to the peak RHR. This type of ratio has also been shown to be related to the time to flashover.[28,29] It would be very desirable in a carpet tile (or in any other product) for such a parameter to be very high. The results are shown in Table 3. For comparison purposes, the value for PMMA plaques, viz. 0·12, is also shown.

In order to try to present some suggestions as to classification categories in levels of TTI/Pk RHR, other fire tests were also used. All carpets were also burned using the NBS smoke chamber test, in the vertical orientation, in the flaming mode. This test was run in case since it is often used to classify carpets, to determine if it would give any useful fire hazard indications. The results are presented in Table 3, in the order of their decreasing maximum smoke density. The other test carried out was the radiant panel to determine the critical radiant flux. These results are presented in Table 4.

The NBS smoke chamber results presented unfortunately do not correlate well with either of the smoke measurements in the cone calorimeter (smoke factor or average extinction area). They do not, in fact, correlate with any other set of cone calorimeter measurements, including the TTI/Pk RHR ratio, discussed above. This means that they could not help to determine breaking points for the classification

TABLE 3
Smoke (NBS Smoke Chamber) and Some Cone RHR Results, at 25 kW/m^{2a}

Carpet tile no.	*NBS D_m (F)*	*SmkFct 5 min (MW/m^2)*	*Av Ext Ar (m^2/kg)*	*TTI/Pk RHR ($s\,m^2/kW$)*	*Pk RHR (kW/m^2)*	*TTI (s)*	*MLRP (g/m^2s^2)*
22	728	1 375	759	0·17	684	114	1·4
7	698	1 003	755	0·18	396	72	2·9
4	643	500	872	0·36	359	131	1·9
20	601	1 630	925	0·16	635	101	1·4
12	573	1 061	763	0·17	521	90	1·9
19	548	1 180	809	0·14	601	84	1·5
13	497	748	510	0·17	531	90	1·8
18	425	842	599	0·15	573	86	2·4
11	378	762	596	0·19	502	95	1·4
10	345	518	470	0·22	487	110	1·7
15	321	574	578	0·22	544	119	1·0
14	305	801	825	0·16	531	84	1·1
8	304	198	259	0·32	441	140	1·1
16	283	248	257	0·15	547	83	1·2
3	269	474	735	0·40	358	142	1·0
1	267	231	639	0·69	222	153	1·3
21	259	698	708	0·33	648	212	1·0
9	235	289	486	0·40	470	186	0·9
5	229	323	636	0·47	368	171	0·9
6	203	240	593	0·42	393	167	1·0
2	195	207	453	0·50	315	159	1·5
17	176	1 099	1 005	0·12	557	69	1·3
PMMA	NMSD	156	97	0·12	450	54	19·8

[a] In order of decreasing NBS D_m (F).

TABLE 4
Critical Radiant Flux and Some Other Carpet Fire Properties

Carpet tile no.	*CRF (W/cm^2)*	*TTI (s)*	*Pk RHR (kW/m^2)*	*TTI/Pk RHR ($s\,m^2/kW$)*	*SmkFct (MW/m^2)*	*NBS F Dm*
2	0·53	159	315	0·50	207	195
4	1·07	131	359	0·36	500	643
8	0·63	140	441	0·32	198	304
10	0·83	110	487	0·22	518	345
13	0·56	90	531	0·17	748	497
17	0·60	69	557	0·12	1 099	176
PMMA	NMSD	54	450	0·12	156	MSD

scheme. It has already been described several times that the results of the NBS smoke chamber do not correlate with those of real fires.[7,13,17–19,21,30] It is thus not surprising that NBS smoke chamber results are not helpful in giving an indication of good fire performance.

Only a few carpet tiles were tested using the flooring radiant panel, to determine one of the other properties often required to assess carpet fire performance: the critical radiant flux (CRF). The results are shown in Table 4, together with a few other results on the same carpet tiles. There is no good correlation between CRF and either the Peak RHR, the inverse of the TTI, or the product of those two. This may be partly due to the fact that there are relatively few values of CRF and that they are fairly close together. Moreover, CRF values are not really designed as measures of fire hazard but as cutoff points to indicate whether the carpet will spread flame along a corridor on its own. In this sense, the test, in conjunction with the methenamine pill test, has clearly helped do a good job in eliminating those carpets that are poor fire performers from the market, as evidenced by the low (or negligible) incidence of examples of carpets having made a large contribution to fire intensity and by the fact that all carpet tiles tested had CRF values above 0·5. Moreover, it appers unlikely that the correlation between CRF values and cone calorimeter values would become much better with many more values, since the cone calorimeter work has suggested that a flux of 10 kW/m^2, as used in the flooring radiant panel, may be too low to be of interest here.

Thus, the results obtained with the traditional carpet fire tests were disappointing for the objectives of this work. It is well known that the cone calorimeter is a good fire test. It is suggested, therefore, that a means of classifying carpet tiles according to their fire performance may be with the cone calorimeter, at an incident radiant flux of 25 kW/m^2 and through the use of the ratio of time to ignition and peak rate of heat release (expressed in s m^2/kW). Thus, that ratio would be the controlling factor for a possible classification scheme, as follows:

$0{\cdot}40 \leq$ TTI/Pk RHR	I
$0{\cdot}20 \leq$ TTI/Pk RHR $< 0{\cdot}40$	II
$0{\cdot}10 \leq$ TTI/Pk RHR $< 0{\cdot}20$	III
TTI/Pk RHR $< 0{\cdot}10$	IV

Using this classification, none, among the carpet tiles tested, showed fire performance in Class IV, although it is known that some other carpets do fall into this class. The following diagram and Fig. 5 show

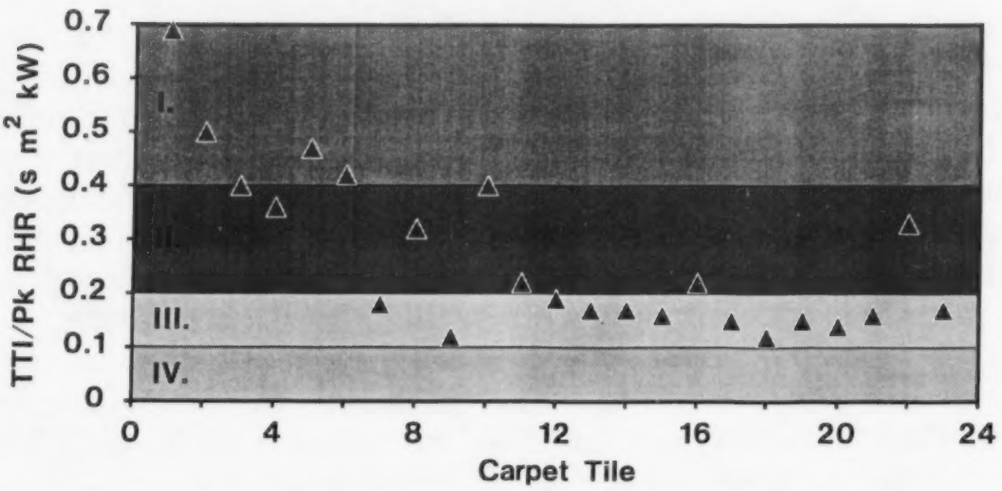

Fig. 5. Range of values found for the TTI/Pk RHR parameter, so as to divide the carpet tiles into classes of fire performance.

the distribution of the carpets according to the classification scheme:

I	1, 2, 3, 5, 6, 9	6 carpets
II	4, 8, 10, 15, 21	5 carpets
III	7, 11, 12, 13, 14, 16, 17, 18, 19, 20, 22	11 carpets

Interestingly, all carpet tiles in Class I have a smoke factor under 500 MW/m^2, and those in Class II have a smoke factor under 700 MW/m^2. The inverse, however, is not true; not all carpet tiles with a low smoke factor are in Class I. The good news, however, is that the lowest smoke factor of all the carpet tiles evaluated into Class III was only 574 MW/m^2.

At the same time, all carpets ranked in Class I also had low D_m in the NBS smoke chamber: all values were under 300. The carpets in Class II ranged in D_m from 300 to 650. However, the carpets in Class III involved several of the lowest values of D_m measured, including the lowest value of all, viz. 176, as well as the highest of all, viz. 728. This indicates again that the smoke chamber results are not really indicative of good fire performance.

Thus, if in addition to time to flashover, smoke obscuration is an issue of overriding interest in a particular application, it would be important to choose carpet tiles with relatively low smoke factors. However, this should not be a consideration other than in the Class I category of carpet tiles.

The six carpet tiles tested in the flooring radiant panel covered all three classes of fire performance: one was in Class I, three were in Class II and two were in Class III. Unfortunately, the carpet tile in Class I was the one with the lowest critical radiant flux.

CONCLUSIONS

The cone calorimeter RHR instrument has been found to be suitable for fire testing of carpet tiles, and to be more indicative of fire performance than the NBS smoke density chamber or the flooring radiant panel.

The tests carried out and an analysis of fire experience suggests that the optimum incident radiant flux to be used for testing carpet tile floor coverings in the cone calorimeter is 25 kW/m^2.

A classification scheme has been proposed, for determining fire performance of carpet tiles, based on the ratio of time to ignition (in seconds) and the peak rate of heat release (in kW/m^2).

$0{\cdot}40 \leq$ TTI/Pk RHR	I
$0{\cdot}20 \leq$ TTI/Pk RHR $< 0{\cdot}40$	II
$0{\cdot}10 \leq$ TTI/Pk RHR $< 0{\cdot}20$	III
TTI/Pk RHR $< 0{\cdot}10$	IV

Additionally, if smoke obscuration was of particular interest in the specific application considered, carpet tiles in Class I could be sub-divided among those with a high and those with a low smoke factor.

Using this classification scheme none of the carpet tiles tested fell into Class IV, although other carpets have been known to do so.

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Characterization of the California Technical Bulletin 133 Ignition Source and a Comparable Gas Burner

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ABSTRACT

The California Bulletin (CB) 133 upholstery ignition source is based on the use of crumpled newsprint. The present work examined the reproducibility of several aspects of this source when placed on an inert chair mock-up. The tendency of this source to heat the side arms of a chair, the area of the seat back subjected to high heat fluxes, the peak flux there and the flux duration all showed substantial variability. For inherently lesser variability a gas burner is preferred. A gas burner, derived from that developed at the British Fire Research Station, was shaped so as to deposit a similar pattern of heat to that of the CB 133 source. The two sources were tested for comparability both on chair mock-ups and on full-scale chairs made from a wide variety of materials. The results indicate that the gas burner, as used here, is a somewhat less severe ignition source than is the CB 133 igniter.

INTRODUCTION

The California Technical Bulletin (CB) 133 test, developed at the California Bureau of Home Furnishings, is a flammability test procedure for seating furniture being considered for possible use in public occupancies (hotels, prisons, nursing homes, etc.).[1] The NIST, Center for Fire Research, in collaboration with the California Bureau of Home Furnishings, recently undertook a study of this test and its procedures with a view toward possible improvements, if the test is to be adopted more broadly. The present paper describes the results of a part of that

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study which was focussed on the CB 133 ignition source and the possibility of developing a comparable gas burner.

The CB 133 test exposes the item of furniture (or alternatively a similar mock-up) to an intense ignition source that is placed in contact with the seat and seat back. The test is conducted within the confines of a prescribed room in which temperatures, gas concentrations and smoke obscuration are measured. There are several failure criteria based on these measurements.[1]

THE CB 133 IGNITION SOURCE

The ignition source used in the CB 133 flammability test procedure is based on crumpled newspaper. Five sheets of paper, each formed into a loose wad, are arranged as shown in Fig. 1. This pile of crumpled paper is covered by a sheet metal and wire mesh box conforming to the specifications shown in Fig. 2. (There are two other variations on this basic box configuration which are to be used with furniture having somewhat uncommon design features; these have not been examined in this study.) Placement of the paper/box combination on upholstered chairs is indicated in Fig. 1. The approximate dimensions of the newspaper sheets and their combined weight (90 ± 5 g) are specified, as is a fixed humidity pre-conditioning. The final specification is that no colored newsprint be included.

The newsprint is ignited with a match, on the left side of the box, about 25 mm from the back and from the seat of the chair. Flames spread over the pile then die down, leaving a mass of smoldering char. The flaming stage typically lasts about 2 min; the smoldering stage can last 5 min or more (the two stages are not cleanly separated). During the flaming stage, flames can extend out both wire mesh sides of the box and up through the slot in the top. These flames are not the only

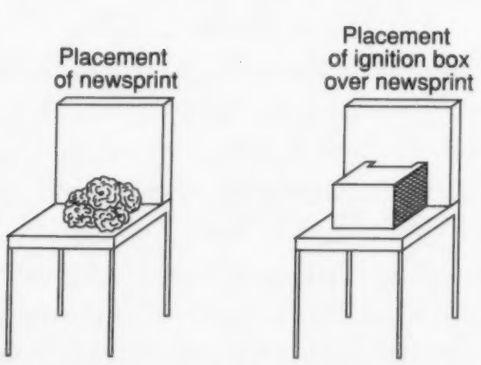

Fig. 1. Configuration and placement of CB 133 igniter.

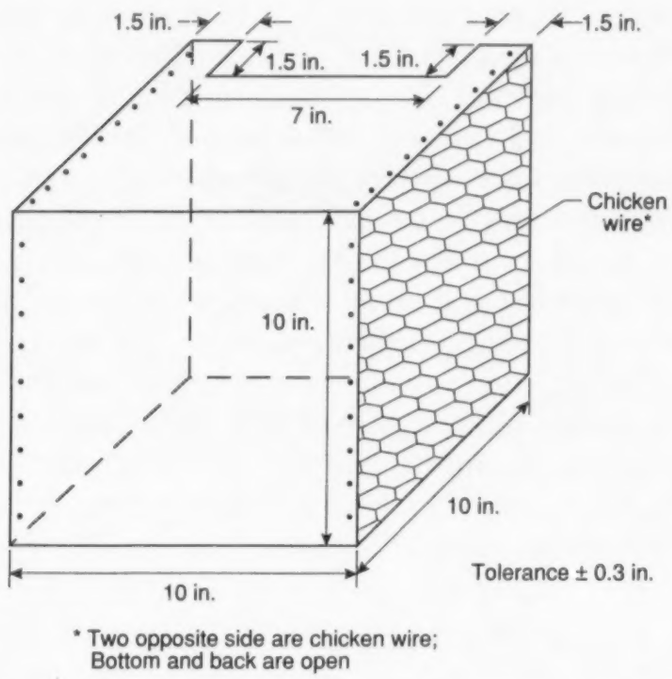

Fig. 2. Details of metal box surrounding crumpled newsprint in CB 133 ignition test procedure. The two sheet metal surfaces are 0·063 mm thick.

source of heat transferred to the furniture surfaces; the brightly glowing paper char is a good radiator, especially when there is a mix of flaming and smoldering.

EXAMINATION OF IGNITION SOURCE REPRODUCIBILITY

Since the geometry of the crumpled newspaper is not precisely reproducible, neither the flaming nor the smoldering stages of its combustion are precisely reproducible. This, in turn, implies that the heating effects which this source imposes on the surfaces of the upholstered furniture may not be the same from one test to the next. These heating effects can be quantified in terms of: (1) the area heated, (2) the flux pattern imposed on this area and (3) the duration of this pattern. An ideal ignition source would be completely reproducible in all of these effects so that scatter in igniter behavior would be eliminated as a potential cause of non-reproducibility in upholstery flammability testing.

This part of the study addressed heating effects of the CB 133 ignition source as seen on inert substrates and the reproducibility of these effects. Because of the complex nature of the source and its heating effects, it has not been possible to fully characterize all of these effects.

It will be seen however, that the heat effects this source imposes are not very reproducible, in an absolute sense. The impact of this non-reproducibility can only be fully judged by applying the source to a series of upholstery substrates of *marginal* ignitability, since the sensitivity to ignition source variability is greatest for these. A broad set of such marginal substrates was not available for use in this study. A set that was more widely varied in its flammability characteristics was utilized for both mock-up and chair studies, as described later.

It is worth noting that the use of inert mock-ups for the characterization of the CB 133 source removes one element of variability. When the newsprint has begun to ignite a combustible substrate, energy feedback from the new flames (mainly radiation) can accelerate the newsprint burning process. This effect can be expected to vary with the nature of the substrate. When the substrate is inert it is minimized.

Flame extension from CB 133 source

As a first step in judging the repeatability of the CB 133 ignition source, as well as the potential extent of the heated substrate area, a simple series of video observations was performed. As noted above, this and subsequent measurements of heat effects were performed on inert substrates. These substrates were placed on the CB 133 mock-up frame shown in Fig. 3. The inert back and seat consisted of a 3 mm thick layer of ceramic felt insulation wrapped around sheets of stainless steel (1·6 mm thick). Here, the side arm frames were present but no material was in these frames. A video camera viewed the box (plus a timer and a

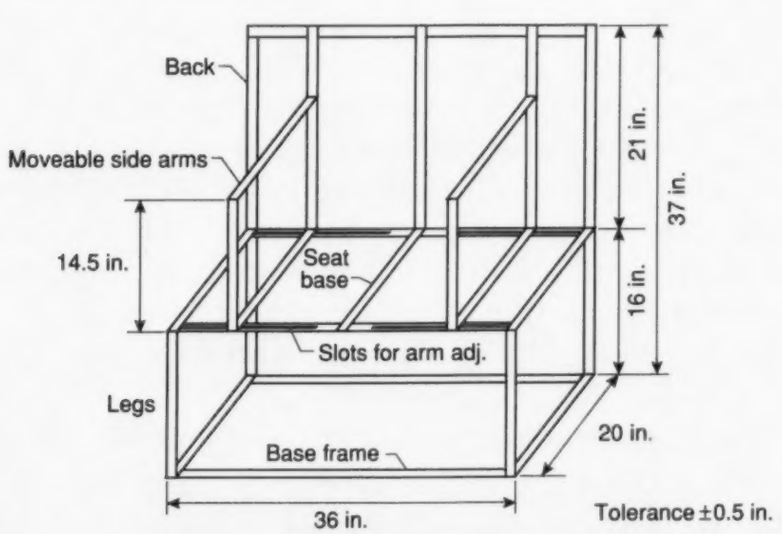

Fig. 3. Chair mock-up frame specified by CB 133 ignition test procedure.

length reference) from a head-on vantage point so that the amount of flame extension out the wire-covered sides and out of the top slot could be accurately measured.

The results, from a limited number of such tests, proved to be highly transient and variable. Figure 4 shows the visible flame area extending from the three sides as a function of time in two nominally identical tests. The large flame area shown extending from the top slot in the left part of Fig. 4 was relatively unusual; it was frequently much less. In fact, the top of the box, with its rather small, slotted opening is what forces flames mainly out the sides by blocking the buoyant plume. The flames out the sides thus tend mainly to emerge near the top of the wire covered sides but they can do so with enough momentum to cause flame impingement on the side arms of a chair. (Here the flames passed through the open side arm frames.)

The transient flickering of the flames, which is responsible for the rapid rise and fall of the flame areas, is not a problem; it is part of the natural behavior of buoyant diffusion flames. What is more problematical is that the time-averaged area tends to vary substantially from one test to the next, even though the initial conditions of the tests are nominally identical. Variability of the side wall flame areas implies variable heating of the side arms of a chair. Variability of the top flame area means the heated area on the back of a chair varies. In the limited number of tests of this type, the average deviation of the side wall flame area was as large as ±65%; for the top flame area it was ±40%.

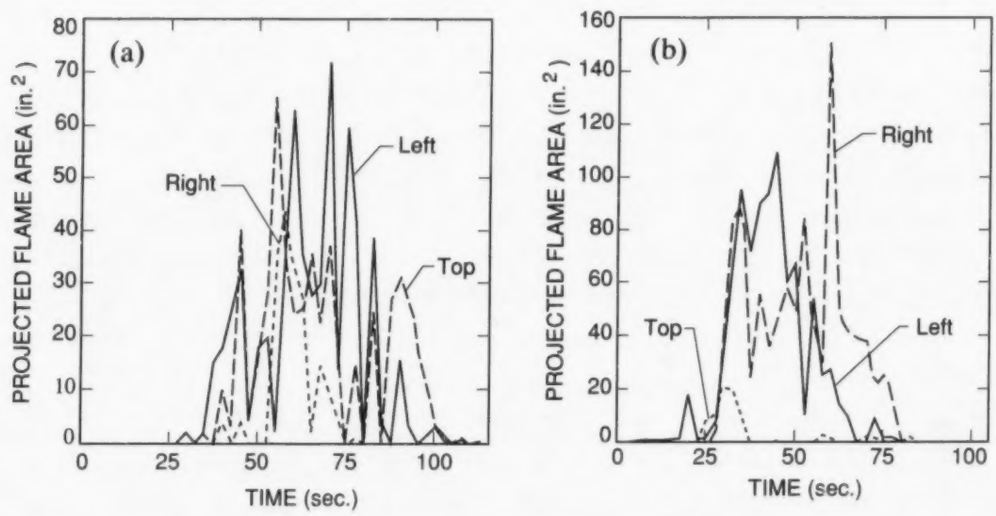

Fig. 4. Projected flame area extending out three surfaces of CB 133 metal box as flames progress from ignition through extinction. Graphs (a) and (b) are from nominally identical tests.

Direct assessment of the heated area on the mock-up seat back

The above results are indicative of the degree of ignition source variability but are not very definitive. Ideally one would like to measure the two-dimensional, time-dependent heat flux pattern which this source imposes on all surfaces of the chair. Measurement of such a pattern on even one surface poses a major problem; there is no device available which can provide a continuous, two-dimensional heat flux measurement. (After the completion of this work, it was brought to the authors' attention that a two-dimensional heat flux gage array has been developed in Finland.[2] The array consists of about 20 individual, somewhat rudimentary, total heat flux gages, each with a time response of about 60 s.) (This problem was dealt with here in two steps which focussed on one mock-up surface—the seat back. First, a semi-quantitative 'picture' of the heat flux pattern was obtained with the aid of infrared thermography. Second, the actual heat flux impinging on the chair back was 'sampled' by placing flux gages at six positions. The infrared thermography is discussed here.

Even though the continuous, two-dimensional heat flux pattern cannot be measured directly, its effects can, at least approximately. A thin sheet of inert material, substituted for the chair back, will heat up in response to impingement of the flux pattern from the ignition source. In the limit of an infinitely thin sheet, the temperature pattern developed in the sheet will be an exact analog of the flux pattern. The thinnest material available for this purpose was a ceramic felt, 0·38 mm thick. The chief drawback in a material this thick is its thermal capacity. It cannot respond with infinite speed to changes in heat flux; cooling is slower than heating. Tests with a gas burner as the heat source indicated that the cooling time of the ceramic sheet (after a period of flame heating) was about 20 s. This, in effect, means that the sheet averages the time-dependent heat flux over a period of this magnitude. The local temperature on the sheet no longer directly reflects the instantaneous flux but rather the flux over the last 20 s or so. This is acceptable here since the principal goal is to compare flux patterns in successive tests, rather than to infer the flux itself.

Figure 5 is a sketch of the arrangement used to monitor the two-dimensional, time-dependent temperature pattern induced in the sheet of ceramic felt by the ignition source. Note that the sheet is viewed from the back side; this means that the flux pattern is somewhat damped also by conduction through the sheet; gas burner tests indicated that this is a significantly lesser effect than the thermal

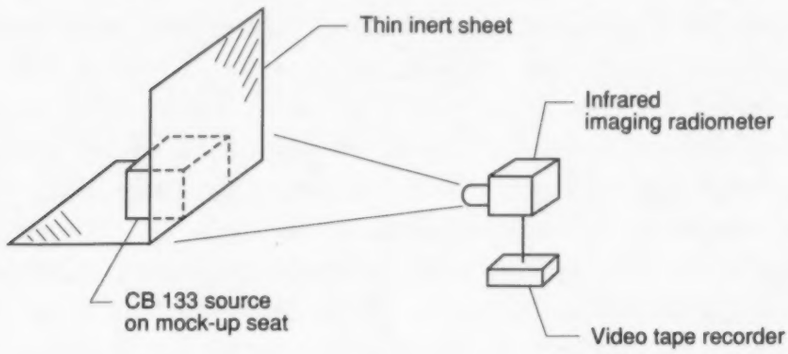

Fig. 5. Schematic of set-up used to obtain infrared images of temperature pattern produced on inert seat back by CB 133 igniter.

capacitance effect mentioned above. Lateral heat conduction in the sheet has minimal effect.

The infrared camera indicated in Fig. 5 is an Inframetrics Model 525 imaging infrared radiometer;† this device is capable of quantitative measurements of two-dimensional surface temperature patterns, if the surface emissivity is known. It can be thought of as an infrared television camera (with somewhat lower spatial resolution than a normal TV camera); it records on video tape the pattern of emitted radiation (8–12 μm) that results from the temperature pattern in the ceramic sheet. By separately recording two black bodies at known temperatures, one obtains a calibration which relates local brightness on the image to local temperature. Actual temperatures are not of direct interest in the present context, but the software package used to analyze these infrared images automatically converts brightness to temperature; this calibration thus keeps the indicated temperatures realistic. In addition, it is possible to estimate the heat flux that corresponds to the measured temperature by means of a simple heat balance on a local segment of the ceramic sheet.

A dozen tests of this nature were run and the time-dependent infrared images recorded. The newsprint in all cases was from a local Washington publication and was somewhat heavier than the CB 133 specification; the total weight of five sheets was approximately 105 g. A conscious effort was made to crumple the paper in a fixed manner for each test.

The infrared video tapes were analyzed with the aid of computer-based infrared image analysis system. This system can grab one to eight

† Certain commercial equipment is identified in this paper in order to adequately specify the experimental conditions. This does not imply endorsement by NIST nor does it imply the equipment is the best available for the purpose.

video frames (1/30 s each) and subject them to various forms of quantitative analysis. In the present case, eight successive frames were averaged to improve the signal-to-noise ratio. These frames show only amorphous glowing regions of varied shape which grow and shrink as the ignition source progresses through flaming and smoldering.

A simple way to characterize these images is provided by the histoplot function. The frame grabber digitizes the image, breaking it into a large number of segments or pixels; the brightness of each pixel is quantified with eight bit resolution. Using the calibration from the two black bodies, mentioned above, the analyzer automatically converts the brightness level of each pixel to an equivalent temperature. A histoplot then displays the number of pixels in the selected image area as a function of temperature. Figure 6 shows the type of result obtained; pixel frequency there is the number of pixels per unit temperature interval. Note that all information on the shape of the heated areas having the various temperature levels is lost in this type of

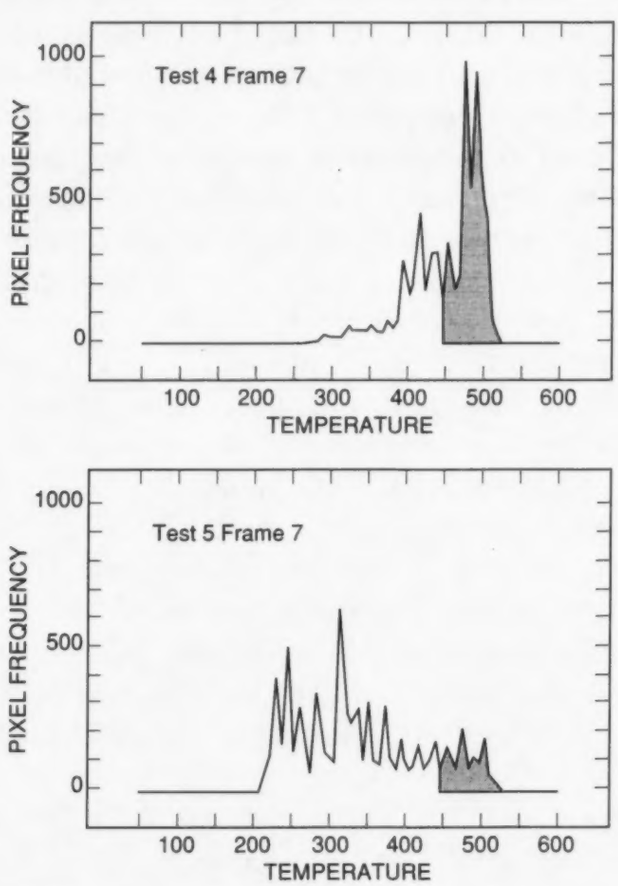

Fig. 6. Histoplots obtained from infrared images at comparable times in nominally identical tests with CB 133 igniter. Shaded area is a measure of the area on the seat back subject to heat fluxes above 4 W/cm^2.

plot. The heated area shapes here, though varied, were not drastically different so that this is not a significant loss.

The results in Fig. 6 are for a fixed numer of frames (and therefore a fixed time) after the first visible heating of the ceramic sheet in response to the ignition source. Thus the upper and lower histoplots, derived from two nominally identical tests, should correspond to approximately equal stages in the development of the flaming on the pile of crumpled newsprint. Clearly the resulting temperature patterns on the seat back of the inert mock-up are not equal. Since temperature is directly related to the impinging heat flux from the ignition source, the flux patterns must be unequal as well. Note the region of each plot above 450 °C (shaded) which, from an energy balance using a surface emissivity estimate of 0·7, corresponds approximately to $\geq 4\ W/cm^2$. The cross-hatched area is a measure of the fraction of the image which is receiving heat fluxes of at least this magnitude. It is obviously much greater in the upper histoplot than in the lower plot. One can repeat such measurements at intervals of 20–30 s (roughly the averaging time of the ceramic sheet, as noted above) throughout the video tapes of a pair of nominally identical tests. The results of such measurements are shown in Table 1. One can see that differences of the order of a factor of two are common. Although not all of the video tapes have been subjected to this tedious form of quantitative analysis, they qualitatively support the conclusion that the area of the seat back subjected to high fluxes by the CB 133 ignition source can vary substantially from test to test.

TABLE 1

Measured Area in Histograms From Infrared Tape Having a Temperature[a] Above 450 °C

Frame [b]	*Area in Test* 1 (cm^2)	*Area in Test* 2 (cm^2)
4	7·8	15·0
5	8·3	15·3
6	14·9	16·9
7	16·4	8·1
8	11·9	6·4
9	12·0	6·6

[a] A temperature of 450 °C corresponds approximately to a heat flux of $4\ W/cm^2$.
[b] The frames are about 20 s apart and each 'frame' is the average from eight successive video frames, each 1/30 s long.

Heat flux measurements at specific locations

As noted above, the infrared radiometer results yield only approximate values of the heat flux on the seat back. It is desirable to have accurate flux measurements but these can be obtained only at a limited number of locations. The infrared images were used to infer a reasonable set of locations that would somewhat emphasize the higher flux regions produced by the ignition source. Six total heat flux gages (Medtherm Schmidt-Boelter type) were arrayed in the seat back as shown in Fig. 7. Note that these are water-cooled gages whose sensor surface remains cool; thus they measure the cold-wall flux, i.e. the impinging flux, not the net flux to the wall during heating. The sensor surfaces were flush with the front surface of the ceramic fiber sheet (3 mm thick for these tests); the holes through the sheet were such as to minimize any hot gas flow through them. The gages were re-coated and re-calibrated whenever their black, high emissivity coating was degraded by deposition of condensate from the burning newsprint.

This flux gage arrangement was used to record the flux-time behavior in five successive, nominally identical tests with the CB 133 ignition source. Figure 8 shows the range of individual results seen; the other tests results fall within this range of peak flux values. In essentially all cases, the flux behavior at all six locations is qualitatively similar. There

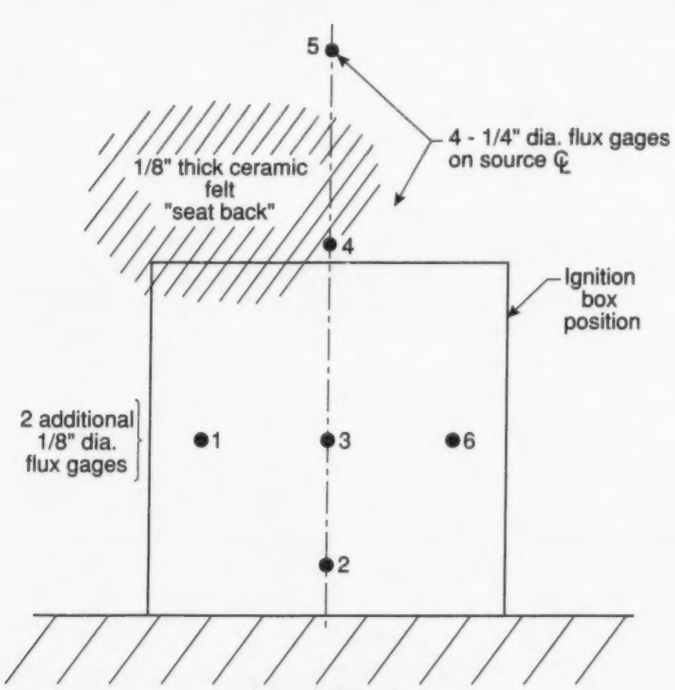

Fig. 7. Placement of heat gages in seat back of inert mock-up.

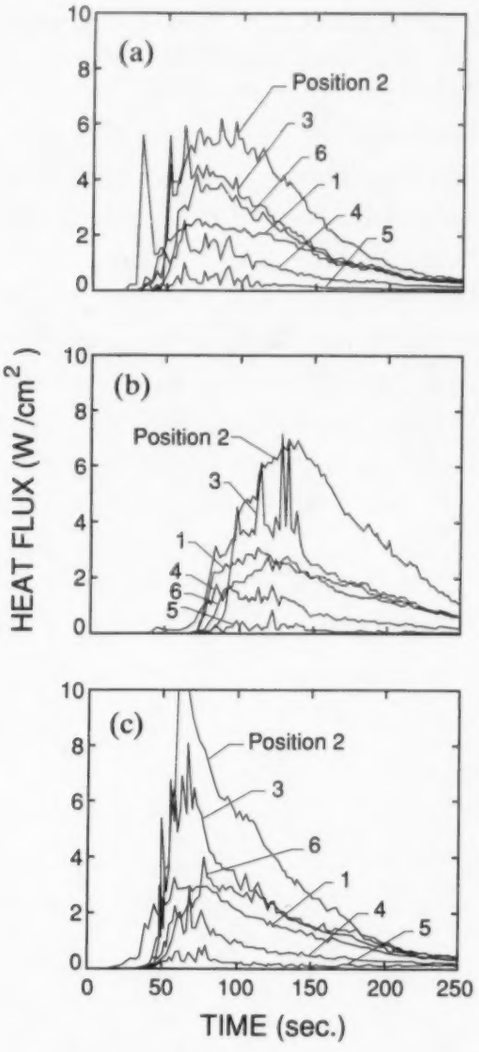

Fig. 8. Heat flux versus time seen at six seat back gage positions in three nominally identical tests with CB 133 ignition source.

is a delay at first as flames spread from the initially ignited area. This is followed by a rapid build-up toward a peak flux that usually occurs at location no. 2; the value of the peak flux there can vary by a factor of two. The long, slow decay in flux level after the peak is a result of the gradual dominance of smoldering and the attendant shrinkage of the charred newsprint. The highly variable fluctuations on this average rise and fall behavior are probably due mainly to flame flickering and attendant fluctuations in char temperature; the 1/10 s response time of the gages allows them to follow such transients with good accuracy.

The average peak heat flux (taken at position 2) is 7·4 W/cm^2 with an average deviation of ±1·3 W/cm^2. This average deviation is not excessively large but the range of peak flux values seen in the five tests (nearly a factor of two) is disturbingly large. At this same position the average time the flux was above half of its maximum value was 80 ± 15 s.

The peak flux levels are quite high relative to gas flames impinging on vertical wall surfaces. There the peak flux is usually in the range from 2·5 to 3 W/cm^2.[3] Most of the difference is very likely due to the high temperature of the newsprint char and the radiation this can produce. Measurements of the char temperature with an infrared thermometer gave values well over 900 °C (assumed char emissivity of unity); a black body of this temperature can emit more than 10 W/cm^2. Interestingly, the peak fluxes reported here are also generally higher than those reported in Ref. 4 for a wide variety of flaming ignition sources used to test upholstery. The reasons for these differences are unclear but probably involve at least two factors. First, flux gage placement relative to the sources is not the same. Secondly, the type of flux gage used may not have been the same. According to the manufacturer (Medtherm, Alabama, USA), Gardon style gages can give lower readings on the same source than Schmidt-Boelter style gages because the surface temperature of the former goes up with increasing flux level.

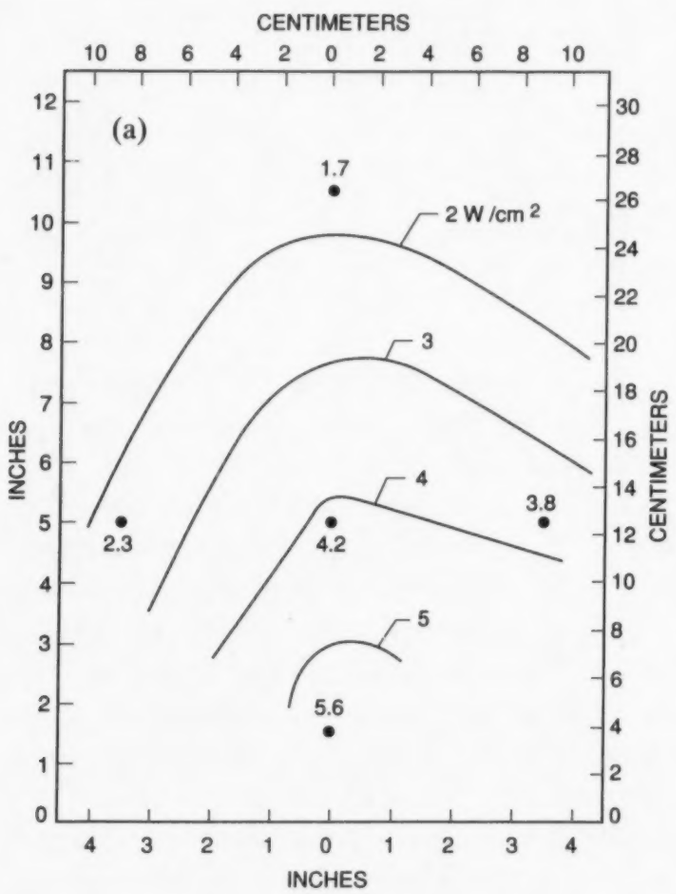

Fig. 9. Iso-flux lines on inert seat back derived by interpolation from data in Fig. 8 at time when position 2 gage is at maximum. Graph (a) here is from (a) in Fig. 8; graph (b) here is from bottom diagram in Fig. 8.

An alternative way to visualize the kind of heat flux results in Fig. 8 is to use them to infer the approximate spatial pattern of flux on the chair back. This pattern is obviously a function of time and the six flux gages do not come close to fully defining this pattern at any given time. However, it is informative to use these limited results to obtain, by linear interpolation, the approximate positions of the lines of constant flux level; Fig. 9 is obtained in this manner from Fig. 8(a) and 8(c), respectively, at a time when each gage is near its maximum reading. (The time chosen is that when the gage in the number two position is about at its maximum. Most of the other gages are peaking at about the same time.) The lines of constant flux are, of course, closed loops but there are insufficient data from the six gages to infer the position of the remaining part of each loop. Inspection of this figure implies that the area enclosed by the lower flux levels did not vary greatly between these two tests which were extremes with regard to peak flux variation. The area enclosed by the higher flux levels ($\geq 5\ W/cm^2$) does vary considerably.

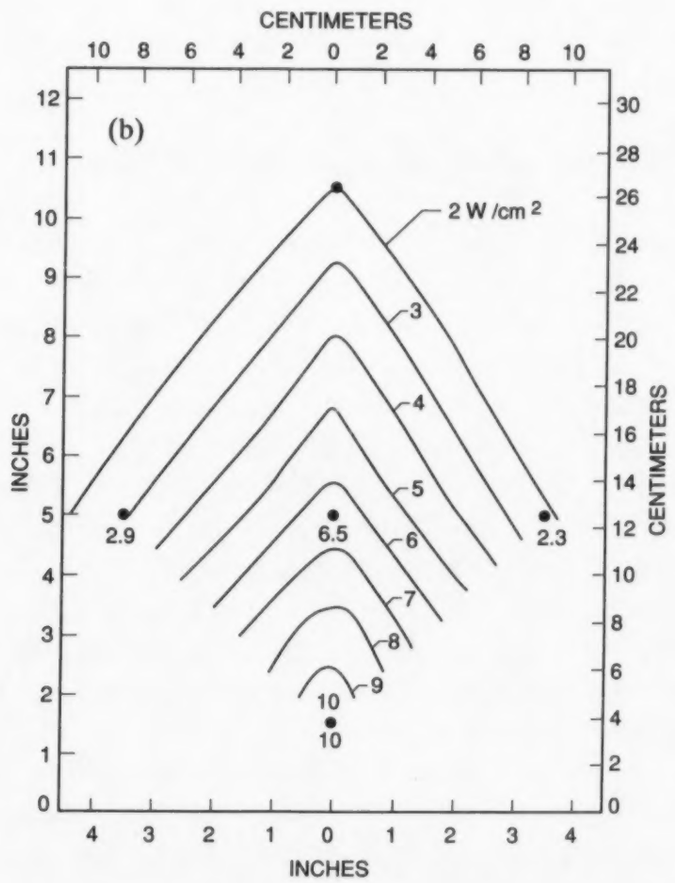

Fig. 9.—*contd.*

Comparison with heat flux from accelerants

To give some perspective to the peak fluxes that the CB 133 source imposes on a chair back, a few tests were run with organic liquid pool fires in a pan on the chair seat. This was intended to represent approximately the type of ignition source that might result from the pouring of an accelerant on the chair seat. The pan was made from stainless steel; it was 30 cm^2 by 1·9 cm deep. It was centered on the chair axis with its back edge 1·3 cm from the seat back. This pan rested inside a second, wider but shallower pan intended to catch any liquid spillover. Both ethanol and octane were burned (400 cm^3) in separate tests. Both types of fuel yielded rapidly fluctuating flames and, thus, fluctuating heat fluxes. Ethanol combustion yields very little soot and its flames are thus relatively weak radiators; the average peak flux was approximately 4 W/cm^2. Octane, a hydrocarbon found in gasoline, is a much stronger soot former; the average peak flux was approximately 8 W/cm^2. While the configuration used here cannot be said to closely represent any realistic arson situation, the results do suggest that the CB 133 source is not out of line with what might be encountered in such situations, at least with regard to peak flux level (heat exposure area and duration will vary with the amount and pattern of a liquid accelerant spill).

Comparison with upholstery substrate ignition data

Another type of perspective on these heat flux data can be obtained by comparing them to the ignition data in Fig. 10 taken from Ref. 5. Those ignition data were obtained on the indicated fabric/substrate combinations in the cone calorimeter; thus the heat flux was radiative and essentially uniform over the 10 cm^2 sample face. The data largely covered the range of commercial upholstery materials in the year they were obtained (1983). Note that the flux scale is in kW/m^2; 10 kW/m^2 equals 1 W/cm^2. Thus a heat flux of 2 W/cm^2 is sufficient to ignite this whole spectrum of upholstery materials in 45 s or less. The CB 133 source greatly exceeds these ignition conditions. Thus it is virtually assured of igniting virtually any flammable upholstery material with which its flames are in contact. The area first ignited can be expected to be tens of square centimeters. Assured ignition of this area does not necessarily mean assured spread of flames beyond this area, especially after the ignition source dies down. Necessary conditions for continued spread of flames on upholstery materials have not yet been derived. This flame spread situation is analogous to, but more complex than, the

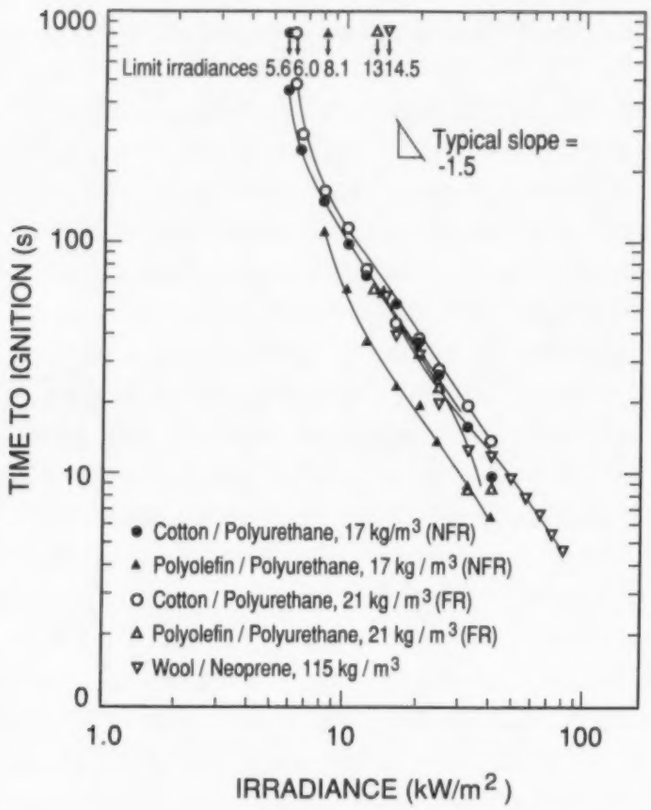

Fig. 10. Cone calorimeter ignitability data from Ref. 5 showing piloted ignition delay time versus incident radiant flux for a variety of fabric/foam combinations.

problem of continued upward spread on vertical walls, which has been addressed with some success.[6,7]

SIMULATION OF CB 133 SOURCE WITH A GAS BURNER

The results in the preceding section indicate that the CB 133 paper-based ignition source varies significantly in the area it subjects to high heat fluxes, in the level and duration of these heat fluxes and in its tendency to heat the side arms of a chair. As was noted above, the impact of this variability will be most fully felt only on marginally failing upholstery where it would lead to non-reproducible results. A suitable array of such upholstery was not available and so a full assessment of the impact of this ignition source variability has not been made.

A gas burner is an inherently more reproducible heat source because the flames are anchored to a series of jets arrayed in a fixed geometry. A gas burner which closely mimics the CB 133 source would be highly

desirable for this reason. Designing a burner which can do this is not a simple task, however. The characterization above of the CB 133 source is incomplete, so the target is not fully defined. Moreover, gas burner flames lack the strong radiation contribution from the glowing paper char in the CB 133 source.

In spite of these difficulties, a more reproducible gas burner source which simulates the CB 133 source was pursued. As will be seen, the result is partially, though not fully successful.

A gas burner cannot be made to mimic the complex, time-varying spread of flames over crumpled paper, followed by a transient glowing char. Instead an effort was made to mimic some of the heat flux characteristics discussed above and to place heat on the same surfaces (seat back, horizontal seat surface, side arm surfaces). Since measurements were not made on any but the seat back surface, the target is well defined only there. The check for comparability thus has been in terms of the net result of application of the two different sources. Ideally, the net result in terms of the burning behavior of an item of upholstery would be the same for either source. The measure of burning behavior chosen here is the rate of heat release curve as the item burns; this is one of the most important factors in measuring the hazard represented by a burning object.[5] Assurance of complete comparability again requires an array of marginally failing upholstery, however, which was not available. Comparability was tested here first by examining heat flux levels from a gas burner (seat back only) and then by comparing rate of heat release results (CB 133 source and the gas burner) with a series of upholstery mock-ups and chairs which covered a broad spectrum of flammability. The broad spectrum of materials was chosen in accord with other goals in the overall furniture flammability study of which this work was a part.

Heat flux characteristics of gas burner

Development of the gas burner proceeded in stages; it began with the burner developed by Ames at the British Fire Research Station.[8] That burner is T-shaped with a series of 1 mm dia. holes that send flame jets both straight down and straight out from the cross-bar of the T. The final burner design used here retained this same arrangement of holes in this region so measurements on the T-burner are relevant here.

The Ames source was tested in the same inert mock-up configuration described above using the flux gage placement indicated in Fig. 11. The burner placement relative to the mock-up surfaces was set with spacers at 50 mm out from the seat back and 25 mm up from the horizontal seat

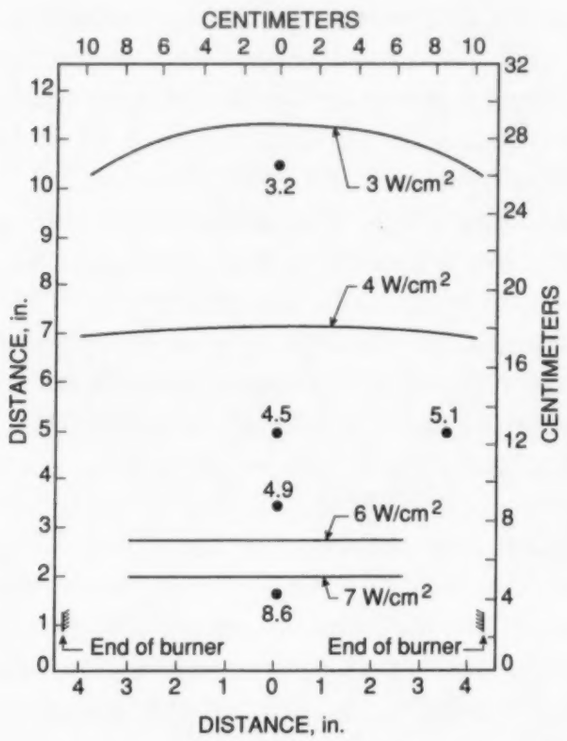

Fig. 11. Iso-flux lines on inert seat back for Ames T-burner operated at 6 liters/min of propane. Lines obtained by interpolation from readings at indicated locations (black dots).

surface; the burner was centered on the mock-up seat. This placement brings the forward facing gas jets into close proximity to the lowest heat flux gage (see Fig. 11). The data in Fig. 11 are for a flow rate of 6 liters/min of propane. The average flux at each gage position is shown along with the linearly interpolated positions of specific flux levels. The flux is actually fluctuating significantly at each gage location (up to ±20–25% with a rough periodicity of 10–15 s) due to the flickering nature of the gaseous diffusion flame. Gas jet impingement is probably why this source is capable of producing an incident flux over 8 W/cm^2 on the lowest gage. Propane is a moderate soot former but the flame thickness with this source is not as great as it was with the liquid octane in the 30 cm pan. Thus it is probable that this high flux comes from enhanced convection (jet impingement) rather than mainly from radiation, as was the case with octane and with the CB 133 source.

Comparison of Fig. 11 with either heat flux pattern in Fig. 9 reveals differences and similarities. Obviously the shapes of the iso-flux lines are different but this is of little consequence. In both figures there is a tendency for there to be small areas of high flux and larger areas of lower fluxes. The actual areas enclosed by high fluxes in Fig. 11 are not

resolved by the limited measurements; those areas in Fig. 9 vary from test to test, as was pointed out before. From this limited comparison on one heated surface it appears that the two sources are not greatly dissimilar.

This T-burner design was modified to more closely mimic the CB 133 source. The goal was to increase the heated chair seat area and to direct flames also toward the side arm positions. Side arm involvement is believed to be an important contributor to persistence of flaming on the upholstery after the ignition source has died down or been removed. The relatively favorable radiative view factor between two flaming surfaces at a right angle to each other should help assure their continued burning.

The final version is shown in Fig. 12. The 'top' of the burner, as seen on the left side of Fig. 12 is identical to the Ames T-burner and the gas flow emitted from the holes in this section is about equal to the 6 liters/min value used above; thus the data in Fig. 11 are pertinent to this final version. One sees in Fig. 12 that the ends of the T have been extended to form a square ring whose outer dimensions are equal to those of the CB 133 box. Along these additional lengths of tube, gas jets are directed inward/downward to ignite the full area enclosed by the ring. Groups of jets on each side also provide flames that can preheat and perhaps ignite the side arms of a chair; these are analogous

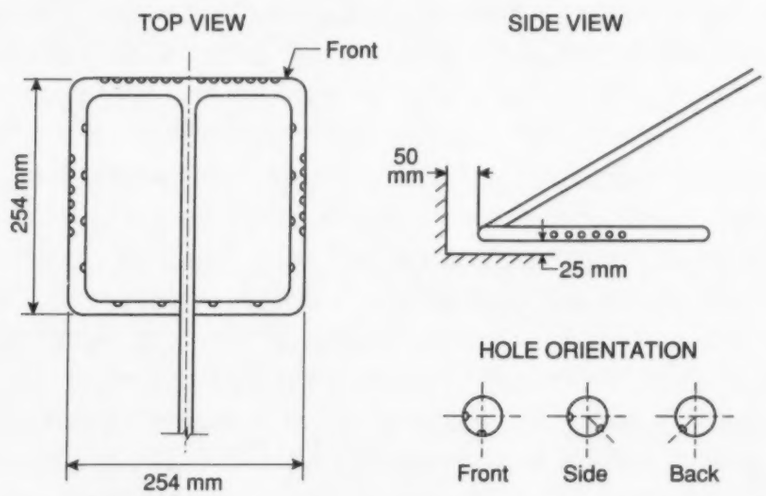

Fig. 12. Schematic of square ring gas burner showing approximate location and orientation of 1 mm dia. holes from which gas jets issue. Gas jets are arrayed as follows: (1) cross-bar of T—14 holes pointing straight out and 9 holes pointing straight down, all with 13 mm spacing; (2) side jets pointing straight out—6 holes each side with 13 mm spacing; first hole is 89 mm from outer edge of T; (3) inward angled jets—4 holes on each of three sides with 50 mm spacing, centered as shown. Burner ring is made from 12·7 mm OD stainless steel. Also shown is placement relative to back and seat of chair, on chair centerline.

to but not identical to the flames coming out the mesh sides of the CB 133 box. Placement is the same as the T-burner.

A question not yet addressed for these gas flame igniters is that of the appropriate gas flow rate and flame duration. Flame duration was chosen on the basis of the CB 133 behavior. Recall that at the flux gage position yielding the highest heat fluxes (position 2 in Fig. 7), the average time the flux was above half of its maximum value was 80 sec. This time was chosen as the gas flame exposure time. Given this it is desirable that the total heat evolved in the gas flame during this time be comparable to the total heat from the CB 133 source (over its entire burn time). For 100 g of dry newsprint, the estimated total heat release is 1·3 MJ; this leads to a flow rate for propane of about 12 liters/min. These conditions of gas flow and flame duration are not necessarily the optimum for simulating the CB 133 source but they are the only conditions used in the comparison tests described below.

COMPARISON OF IGNITION SOURCES ON MOCK-UPS AND FULL-SCALE CHAIRS

The rate of heat release response of both fabric/cushion mock-ups and full-scale chairs was measured in the NIST Furniture Calorimeter facility. Each combination of materials was ignited, in separate tests, by the CB 133 source and by the gas burner employed as described above. The material combinations are given in Table 2; further details of these can be found in Ref. 9.

Upholstery mock-ups

Seven combinations of these materials were investigated in mock-up upholstered cushion form. The material combinations were based upon two foams, melamine-treated polyurethane foam and California 117 polyurethane form, a fiberglass interliner, and two fabrics, nylon and wool. The material combinations investigated were A through F plus K, in Table 2; the most flammable (polyolefin) and least flammable (PVC) fabrics were not included. Note that combinations A–B, C–D and E–F differ only in the presence or absence of the fiberglass interliner. The combination A–K differs only in the type of foam.

A single furniture manufacturer supplied the fabrics, foams for the mock-up tests and chairs for the full-scale tests.

The mock-up cushions and the mock-ups themselves were assembled in accord with Ref. 1, using the frame shown in Fig. 3; the foam blocks

TABLE 2
Material combinations used in igniter comparison study

Designation	*Materials*[a]
A	Wool fabric/Calif. 117 PU foam[b]
B	Wool fabric/fiberglass liner/Calif. 117 PU foam
C	Nylon fabric/melamine-PU foam[c]
D	Nylon fabric/fiberglass liner/melamine-PU foam
E	Nylon fabric/Calif. 117 PU foam
F	Nylon fabric/fiberglass liner/Calif. 117 PU foam
G	PVC fabric[d] Calif. PU foam
H	PVC fabric/melamine-PU foam
I	Polyolefin fabric/fiberglass liner/Calif. 117 PU foam
J	Polyolefin fabric/Calif. 117 PU foam
K	Wool fabric/melamine-PU foam

[a] Each time a material is referred to, it is the same material, i.e. the nylon is always the same nylon, the wool is the same wool, etc.
[b] This polyurethane foam passes the small flame ignition-resistance test specified in California Technical Bulletin 117.
[c] This is a 48·1 kg lm^3 (3 lb/ft^3) polyurethane foam containing melamine as a flame retardant.
[d] This is a special, flame-resistant grade of PVC fabric.

were 70 cm squares by 10 cm thick. Four cushions were used in each mock-up providing a seat, a back and two side arms. The two vertical cushions forming the side arms extended down past the full depth of the seat cushion. The vertical back seat cushion was positioned above the horizontal seat and was wired to the metal frame to hold it in place.

Duplicate tests were run with each of the two ignition sources for a total of 28 mock-up tests. The gas burner was placed as described above and run with 12 liters/min of propane for 80 s. It was removed at the end of this interval. The CB 133 box remained in place throughout a test, as per the CB 133 test protocol.

Table 3 summarizes the salient features of the results for the seven mock-up combinations. The total heat release and the percent weight loss columns both give an overall picture of the consequences of the igniter application. From these one sees that there was a variety of behavior exhibited by the various material combinations as elicited by the two igniters, from ignition resistance to total consumption.

Two of the combinations, B and K, were relatively resistant to both types of ignition source, however, the CB 133 source yielded a late-developing fire with one of the K mock-ups (see time of peak heat release).

Late-developing fires in the mock-up tests, i.e. those which develop

TABLE 3
Mock-Up Test Results

Fabric/linear/foam 'designation'	*Ignition source*	*Moving average peak heat release*[a] *(MW)*	*Time of peak heat release (s)*	*Total heat released (MJ)*	*Weight loss (%)*
Wool—California 117 'A'	CB 133[b]	0·59	245	105	92
	CB 133	0·74	280	108	92
	Burner[c]	0·63	210	97	87
	Burner	0·55	200	58	84
Wool—fiberglass—California 117 'B'	CB 133	0·07	110	21	2
	CB 133	0·01	90	2	0
	Burner	0·07	75	17	1
	Burner	0·01	75	2	1
Wool—melamine 'K'	CB 133	0·15	1020	92	41
	CB 133	0·01	190	1	1
	Burner	0·03	80	3	1
	Burner	0·05	100	8	1
Nylon—California 117 'E'	CB 133	0·78	195	151	96
	CB 133	0·85	185	147	96
	Burner	0·69	140	121	99
	Burner	0·71	150	121	95
Nylon—fiberglass—California 117 'F'	CB 133	0·73	320	162	100
	CB 133	0·61	290	125	88
	Burner	0·74	300	127	93
	Burner	0·69	310	130	100
Nylon—melamine 'C'	CB 133	0·26	425	114	56
	CB 133	0·27	370	124	56
	Burner	0·17	520	66	41
	Burner	0·14	530	54	35
Nylon—fiberglass—melamine 'D'	CB 133	0·36	1620	126	92
	CB 133	0·37	950	120	80
	Burner	0·16	200	147	13
	Burner	0·14	210	59	13

[a] Moving average calculated over a 60 s period to reduce noise level.
[b] CB 133 newspaper ignition source.
[c] Propane gas burner ignition source.

many minutes after the igniter flames have died out, are problematical with regard to interpretation. In some, but not all, cases they seem to be due to the mock-up configuration which leaves part of the back of the foam block exposed. Combination D, which incorporates a flammable nylon fabric on top of a fiberglass liner poses conditions

susceptible to late ignition. The nylon burns slowly but continually until the flames reach the area of the back of the cushion which is not protected by the fiberglass. Curiously, though the same sequence was initiated with combination D by both the CB 133 source and by the gas burner, only the former source led to foam involvement and a relatively large fire. The disparity in ignition consequences for combination D, though reproducible, seems dependent on peculiarities of the mock-up.

The late-developing fire in one test of combination K, mentioned above, did not involve slow flame spread around a barrier layer. Rather, there seemed to be some interaction between the substrate and the smoldering newspaper char which grew slowly into an extensive late fire. The fact that this occurred in only one of the CB 133 igniter tests is an indication of irreproducibility of that source.

Certain material combinations yielded fairly comparable rate of heat release curves for both igniter types; these included combinations A, E and F. What these materials have in common is that, in these tests, flames ignite and spread readily over the material while the igniter flame is present (persisting after it dies). In the limit of a material highly prone to such behavior, flames would spread away from the igniter and become independent of it early in the ignition exposure and the response of the material would become insensitive to the igniter characteristics. Thus, comparable heat release rate curves for such flammable combinations are reassuring in that they indicate no unexpected new phenomana have entered in but this comparability does not prove ignition source equality.

Figure 13 shows sets of rate of heat release curves for three of the materials combinations. (It is worth noting that the heat from the ignition sources is generally small on the scale of the heat release rate curves; they are about 15 kW.) The upper and middle sets show examples of good comparability; the lowest set, for combination C, reveals significantly different behavior, dependent on the ignition source. With combination C the CB 133 source seemed more readily able to ignite the inner surface of the sidearms of the mock-up and the intensity of the fire on the seat cushion, early in the test, was greater. The net result was an earlier, more intense fire.

The differences in rate of heat release behavior, while seen with only a limited number of the material combinations in the mock-ups, all are such as to indicate that the gas burner is a somewhat less severe ignition source. Since some of the differences seem possibly to be due to the mock-up configuration itself, it is important to examine also ignition source comparisons made with actual chairs.

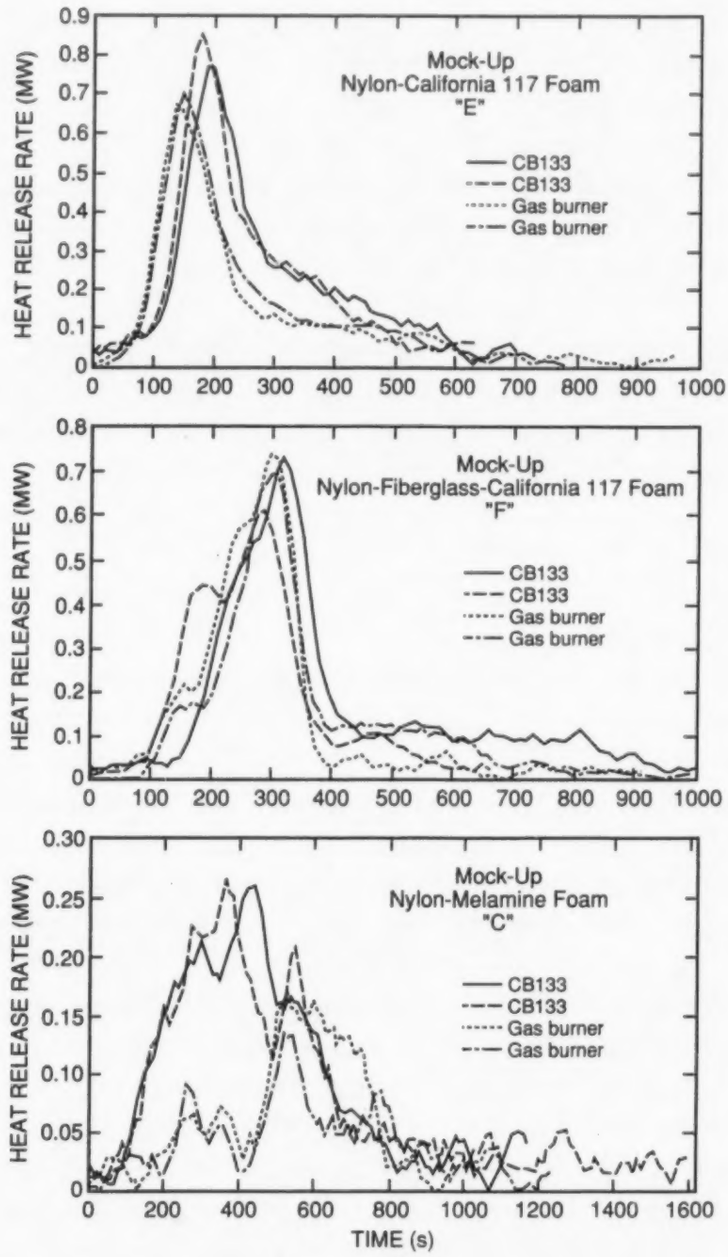

Fig. 13. Rate of heat release versus time from three material combinations in mock-up form. Results from two tests each with the two ignition sources. Note the differing scales on the graphs.

Full-scale chairs

Upholstered chairs were specially ordered from a commercial manufacturer in material combinations A through J (see Table 2). All chairs had the same geometry, as shown in Fig. 14. The chair consists of a solid hardwood frame, with foam padded arms, foam block seat and seat back. No cotton or polyester batting wraps were utilized in the

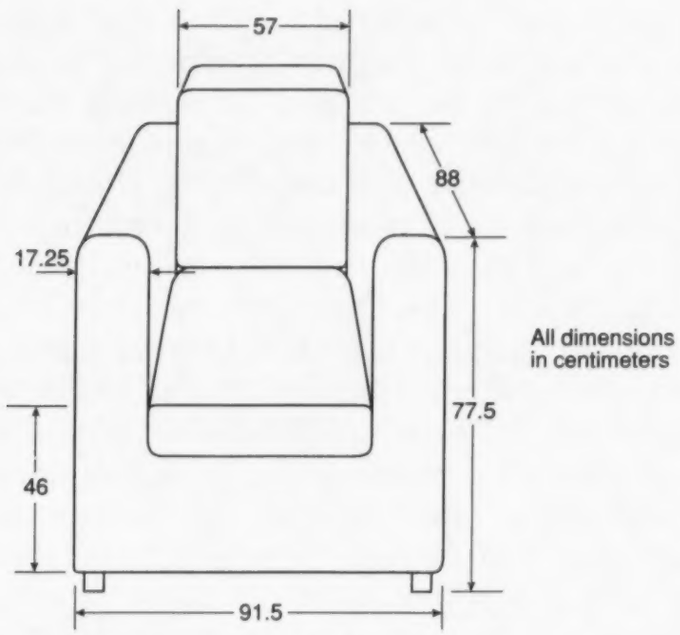

Fig. 14. Schematic of chair design for full-scale tests.

construction of these chairs. The support system consists of a custom coil foundation. The two foam block cushions can be physically removed from the chair: the back cushion, 57 cm wide, 36 cm high and 12 cm thick, and the seat bottom cushion, 57 cm wide, 66 cm long and 12 cm thick.

The combinations utilizing the fiberglass interliner required special assembling. The interliners of the back and seat bottom cushions were sewn with fiberglass thread to assure that the thread would not melt during exposure to the ignition source. The sewing of the liners with the fiberglass thread was done at the Center for Fire Research. The stitches were sewn at approximately 7 stitches/2·5 cm on a sewing machine. In contrast to the situation with the mock-ups, the chair cushions were totally enclosed by the fiberglass liner material. The chair assembly consisted of a foam sheet placed directly onto the chair frame and stapled into place. If a fire barrier was utilized, the fiberglass interliner was placed on top of the foam and attached to the chair frame with the use of a staple gun. Lastly, the selected fabric was secured to the chair frame. Thus, all exposed surfaces of the chair were encased by the fiberglass interliner.

Because of the limited number of chairs available in this part of the program, only a single test was run in the authors' furniture calorimeter facility with each igniter in each chair combination. The issue of repeatability is thus left unanswered.

It should be noted that the width of the chair seat is significantly less than that of the mock-up seat. This can be expected to change the heat flux to the inner surface of the side arms. It is likely that the extent of the change depends on which ignition source is used. The flux to the side arms is a mix of radiation and convection. Unless that mix is the same for both sources, and is produced by geometrically comparable hot zones, it is unlikely that the flux will vary in the same way with distance from the source. This illustrates the considerable difficulty inherent in attempting to mimic the CB 133 source with a gas source.

Table 4 summarizes the main features of the results with the chair tests. Once again the material combinations yielding early ignition and flame spread gave good comparability in overall behavior between the two ignition sources. These include combinations A, C, E and J; Fig. 15 includes the heat release curves for combination E. It is interesting to note that combination C, which gave a significant difference between ignition sources when tested in the mock-up form did not do so in the chair form. In the chair, both igniter types gave very similar slowly developing fires analogous to that seen with the gas burner on the mock-up of this material.

Combination B gave comparable behavior for both igniter types; only minimal fires developed for both. Combination I gave late-developing fires with both igniters; the fires were somewhat different in intensity (peak heat release rate) and occurred at differing times. Since late-developing fires are subject to some randomness due to their marginal occurrence, this amounts to fairly good comparability for combination I.

Combinations D and H, both of which yielded only weak fires in these tests, show what appear to be significant differences with the two ignition sources (see Fig. 15). In the case of combination D, the gas burner gave a lower peak heat release rate and a lesser total heat release. Note that the fires with both of these material combinations were not very severe. Note that combination D gave two late-developing fires when subjected in mock-up form to the CB 133 source. The fact that this did not happen in the chair configuration (where all foam surfaces were fully covered with fiberglass) supports the idea, suggested above, that the open area on the back of the mock-up cushions was responsible for the late fires there.

Combination H is the one exception to the general trend seen here in which the CB 133 source generally gave a more severe fire for material combinations showing igniter-dependent behavior. This combination was not tested in mock-up form. The lesser severity of the fire with the CB 133 source in the one chair test of this type is clearly due to the fact

TABLE 4
Full-Scale Chair Test Results

Fabric/liner/foam 'designation'	*Ignition source*	*Moving average peak heat release*[a] *(MW)*	*Time of peak heat release (s)*	*Total heat released (MJ)*	*Weight loss (%)*
Wool—California 117 'A'	CB 133[b]	1·15	310	459	85
	Burner[c]	1·11	310	448	89
Wool—fiberglass—California 117 'B'	CB 133	0·03	100	7·9	0
	Burner	0·03	79	4·3	0
Nylon—California 117 'E'	CB 133	1·50	361	460	92
	Burner	1·52	313	462	89
Nylon—fiberglass—California 117 'F'	CB 133	0·40	1870	400	81
	Burner	0·11	100	18·3	4
Nylon—melamine 'C'	CB 133	1·15	848	499	87
	Burner	1·16	831	446	91
Nylon—fiberglass—melamine 'D'	CB 133	0·09	129	30	2
	Burner	0·04	154	39	3
PVC fabric—California 117 'G'	CB 133	0·72	1830	422	84
	Burner	0·16	69	12·6	3
PVC fabric—melamine 'H'	CB 133	0·08	61	6·3	1
	Burner	0·14	51	7·5	1
Polyolefin—fiberglass—California 117 'I'	CB 133	0·47	1690	396	82
	Burner	0·67	4430	434	89
Polyolefin—California 117 'J'	CB 133	1·72	230	494	89
	Burner	1·65	222	436	93

[a] Moving average calculated over a 10-s period.
[b] Newspaper ignition source.
[c] Propane gas burner.

that only one side arm ignited, not both, as with the gas burner. The repeatability of this result is undetermined.

In contrast to combination C which gave good comparability between igniters in the chair form but not in the mock-up form, combination F

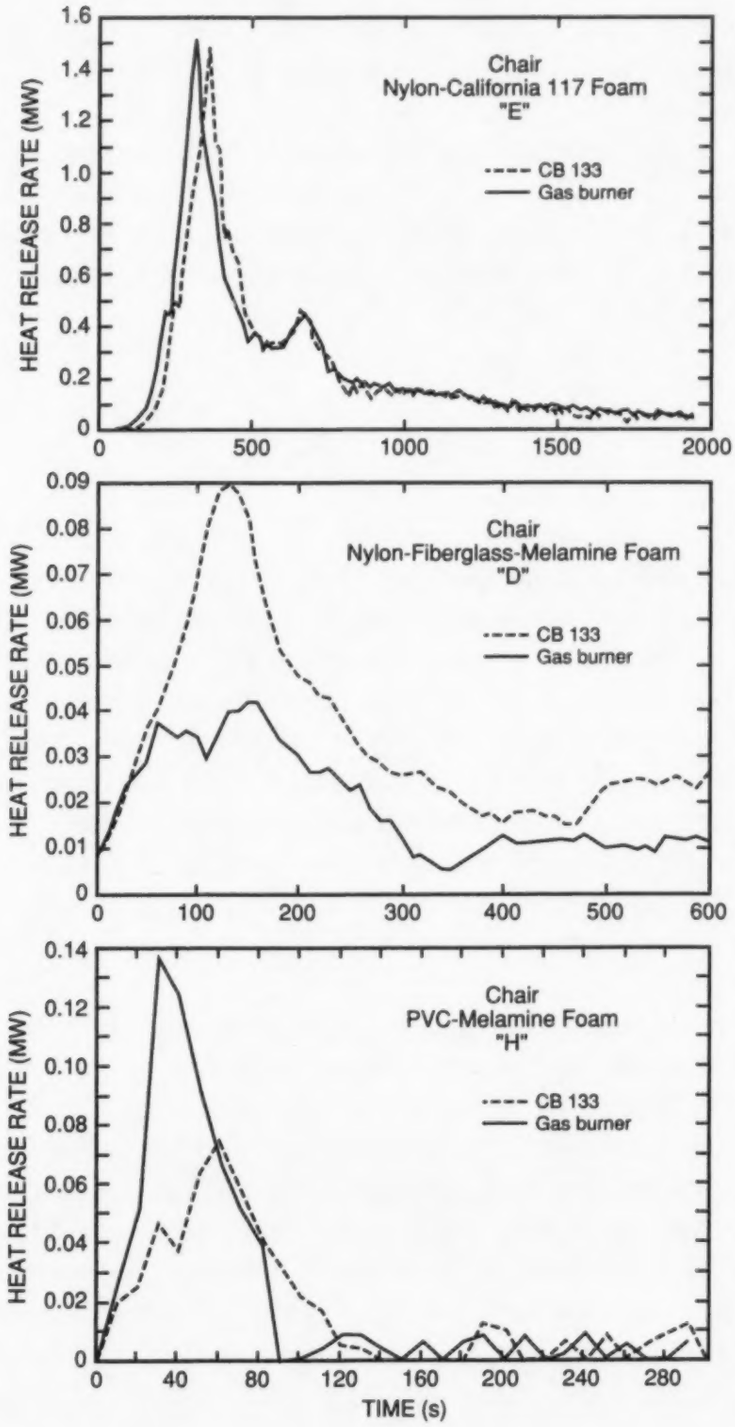

Fig. 15. Rate of heat release versus time from three material combinations in chair form. Results from one test each of the two igniters. Note the differing scales on the graphs.

did the opposite. The poor igniter comparability in the chair form was mainly due to a late-developing fire with the CB 133 ignition source but even during the igniter flaming period the CB 133 source elicited more than twice as much heat from the substrate. The reason for this is not known but may be a consequence of the variability of the CB 133 source.

Finally, it is noted that combination G, which was not tested in mock-up form, gave a late-developing fire only when subjected to the CB 133 source in chair form. Thus, both combinations F and G add to the indication that the gas burner is a somewhat less severe igniter than the CB 133 igniter.

CONCLUSIONS

The measurements reported here indicate that the CB 133 newspaper-based ignition source is subject to appreciable variability in its effects on the side arms of a chair, in the area of the seat back that it subjects to high heat fluxes and in the level and duration of the peak flux on the chair back. Nevertheless, there will be many upholstery combinations for which this variability is irrelevant, either because these combinations are so flammable or so non-flammable that the changes in ignition source behavior elicit no significant difference in overall response. For upholstery material combinations in the middle this source variability can be expected to lead to non-reproducible results and the consequent need for repeated tests (or potentially deceptive results from single tests).

The gas burner tested here attempts to distribute heat on the surfaces of a chair or mock-up in a manner similar to the CB 133 source. Unfortunately, in this program measurements could be made only on the chair back. This is the surface of most rapid spread so it is important to match the heating characteristics on this surface. The gas burner does this reasonably well.† However, the comparison testing of the two sources, both on mock-ups and on actual chairs, generally (with one exception) implies that the gas burner is a less severe ignition source overall. For marginally ignitable substrates, which are those

† Since completion of this work, it has come to the authors' attention that certain substrates, e.g., those involving a *thick* layer of polyester, can melt away beneath the gas burner and ultimately escape its effects. In contrast, the CB 133 box will sink down into such substrates and ignite them. The gas burner could be made to sink similarly if it were free to pivot about a mounting point and counter-balanced so that it imposed a weight equal to the CB 133 box on the chair surface.

most sensitive to igniter variation, the gas burner in some cases yielded a lesser total heat evolution then the CB 133 igniter and, in other cases, no sustained ignition at all, whereas the CB 133 igniter yielded late-developing fires. The comparisons do not suggest major differences but differences which are significant nonetheless.

It is worth noting that, while the gas burner is a more reproducible ignition source, it must be properly maintained. The gas jets are emitted from numerous small holes (1 mm dia.) which could be partially blocked by soot or other solid/liquid combustion products. The holes must be cleaned after every test with a rod of material which will not alter the hole size.

The gas burner could presumably be made more comparable to the CB 133 source. Two simple ways to increase its severity are to increase the gas flow rate and to increase the burning duration. The detailed behavior seen in some of the tests suggests, however, that the needed changes are more subtle. The flux to the chair seat may be too low and the radiative component of the heat incident on the chair surfaces may be too low, as well, leading to a substantially different flux versus distance dependence than that given by the CB 133 igniter. Both of these issues could be addressed simultaneously by going to a gas with a stronger sooting potential, but it is not clear that true comparability could be achieved this way. In any event, comparability can only be firmly demonstrated by undertaking a large chair testing program utilizing a variety of marginally ignitable substrates in several geometries.

ACKNOWLEDGMENTS

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Fire Detection Using Cross-Correlations of Sensor Signals

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ABSTRACT

Experiments have been carried out to investigate the efficacy of signal cross-correlation techniques to provide early detection of fire. Cross-correlations were of the form $\langle A \cdot B \rangle$ *and* $\langle A \cdot B \cdot C \rangle$, *where A, B and C were signals from various sensors and* $\langle\ \rangle$ *denotes averages of signal products over a correlation time interval,* τ_C, *extending from present time into the past. All signals were referenced to their baseline averages extending over a time interval,* τ_B, *into the past. Tests were conducted in a room, quiescent or highly ventilated, using fire sources modeled on the test fires of European Standard EN*54. *Various sensors responded to airborne pyrolysis and combustion products. Two complementary cross-correlations,* $\langle \Delta CO \cdot \Delta ION \rangle$ *and* $\langle \Delta CO_2 \cdot \Delta T \rangle$, *were shown (with* τ_B *selected in the range* 100–250 *s and* τ_C *selected in the range* 10–25 *s) to be equivalent to a much more sensitive detection system than implied by the limits of the most sensitive EN*54 *class, where* ΔCO *and* ΔCO_2 *are referenced carbon monoxide and carbon dioxide concentrations,* ΔION *is the referenced output of a measuring ionization chamber, and* ΔT *is the referenced temperature.*

NOTATION

A (B, C)	Symbolic sensor signals
A_0	Baseline value of signal A
CO	Carbon monoxide concentration by volume
CO_2	Carbon dioxide concentration by volume

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d	Optical path length (m)
H	Room height (m)
I	Ionization chamber current with smoke (A)
I_0	Ionization chamber current without smoke (A)
ION	Voltage output of measuring ionization chamber (V)
m	Optical smoke density, eqn (8) (m^{-1})
OD	Optical density (extinction coefficient), eqn (7) (m^{-1})
ODB	Optical density at 'blue' wavelength, 457·9 nm (m^{-1})
ODI	Optical density at 'infrared' wavelength, 905 nm (m^{-1})
ODR	Optical density at 'red' wavelength, 632·8 nm (m^{-1})
ODV	Optical density from vertical laser beam in room, 632·8 nm (m^{-1})
SCT	Voltage output of light scattering meter (V)
t	Time (s)
t_n	Time of (past) scan n (n negative) (s)
t_0	Current scan time (s)
T	Temperature (°C, K)
THC	Total hydrocarbon concentration by volume
V	Photodiode voltage output with smoke (V)
V_0	Photodiode voltage output without smoke (V)
y	Ionization smoke density, eqn (6)
δ	Change in quantity from initial value
Δ	Deviation in instrument output from baseline value
τ_B	Baseline time interval (s)
τ_C	Correlation time interval (s)
τ_D	Relative delay time of two signals (s)
τ_s	Time between scans (s)

INTRODUCTION

State-of-the-art fire detectors typically monitor a single component of the fire products, such as smoke particles or heat. Examples are photoelectric scattering and obscuration detectors, ionization detectors, and cloud chambers for smoke particles, and fixed temperature and rate-of-temperature-rise detectors for heat. In principle, it is possible to make these detectors very sensitive to fire conditions. However, they would then also become very sensitive to nonfire conditions, including electronic noise, resulting in intolerable susceptibility to false alarm. For example, very sensitive heat detectors would respond to common, everyday temperature drifts and transients in the environment. Smoke

detectors already on the market tend to be too sensitive to nonfire conditions in many installations, making it difficult to devise designs of the desired high sensitivity to very early fire conditions.

A way of lowering the detection threshold in the presence of noise, with enhanced discrimination against false alarms, is to employ the principle of cross-correlation between two or more signals generated by fire at a given spatial location. For example, to define a state of alarm under this principle, one might require that a time-averaged product of two signals from the fire exceed a threshold, where one signal might be generated by particulates and the other by heat. Few nonfire sources generate both particles and heat and contributions from electronic noise will tend to 'correlate out', which greatly limits the nonfire or false alarms relative to a detection strategy based on either fire product alone.

The correlation method had not been tested experimentally prior to this investigation, the purpose of which was to explore the capability of the method in various forms. The investigation was intended as a generic study, incorporating, for the most part, commercially available sensors and components, fairly common sampling techniques, and a limited number of pyrolysis and fire products.

The principle of cross correlation of signals from different sensors has already been proposed in a recent US patent.[1] This patent specifically considers correlations of signals from a heat detector and a light detector, including circuitry for comparing the correlation magnitude with a threshold for alarm. The methods of the current investigation were not bound by any procedures discussed in that patent.

Many contributions exist in the fire detection literature on signal algorithms to limit the frequency of false alarms. A recent contribution is that of Ishii *et al.*[2] on processing of signals of multiple sensors to improve the reliability of detection. Another is Okayama's work[3] on establishing the state of alarm from analog sensor systems using neural nets. Luck[4] has discussed application of correlation filters in signal detection algorithms. However, there appear to be no publications discussing signal cross-correlations, *per se,* as a basis for establishing the state of alarm.

A detailed account of this work is available.[5]

DISCUSSION OF CONCEPT

The time-averaged product, or cross-correlation, of two continuous signals, A and B, is a function of (present) time, t, and the averaging

interval back in time, τ_C. It can be written:

$$\langle A \cdot B \rangle(t, \tau_C) = \tau_C^{-1} \int_{t-\tau_C}^{t} A(t')B(t')\,dt' \tag{1}$$

where the left hand side represents the average of the signal product $A \cdot B$ which is a function of t and τ_C. The cross-correlation will remain small as long as A and B vary independently and will increase when A and B increase together. Random electronic noise contributions from A and B will tend to cancel. The longer the averaging interval, the more reliable will be the cross-correlation for assessing whether fire products are present. However, the effective speed of response of the system will decrease with increasing averaging times.

Instruments used to monitor components of the fire environment may have built-in delays associated with transport of the sample. If the delay times for the selected signals differ, the maximum correlation of the signals with respect to the relative delay time, τ_D, should be sought, where the correlation is expressed:

$$\langle A \cdot B \rangle(t, \tau_C, \tau_D) = \Delta t^{-1} \int_{t-\tau_C}^{t} A(t')B(t' + \tau_D)\,dt' \tag{2}$$

The average product, $\langle A \cdot B \rangle$, would be processed for various relative delay times, τ_D, until a maximum for the interval $t - \tau_C$ to t is established.

If higher orders of discrimination are desired than afforded by two signals, one may define triple correlations, $\langle A \cdot B \cdot C \rangle$, where C is a third signal, or correlations of still higher order.

Equations (1) and (2) assume that signals A and B are continuous in time. Analogous equations can be written for discrete signal data at finite scan rates, involving sums of products over the averaging intervals. An equation equivalent to eqn (1) is:

$$\langle A \cdot B \rangle(t_0, \tau_C, \tau_s) = (\tau_C/\tau_s)^{-1} \sum_{n=0}^{-(\tau_C/\tau_s - 1)} A(t_n) \cdot B(t_n) \tag{3}$$

where t_0 is present time (last scan); t_n is the time of past scan n; τ_s is the time between scans; $(\tau_C/\tau_s - 1)$ is an integer corresponding to the number of scans into the past to the beginning of the correlation interval; and $(\tau_C/\tau_s)^{-1}$ is the number of scans in the correlation interval, including the last scan. The correlation is a function of (present) time (t_0), the length of the correlation interval (τ_C), and the time between scans (τ_s). An equation equivalent to eqn (2) is:

$$\langle A \cdot B \rangle(t_0, \tau_C, \tau_s, \tau_D) = (\tau_C/\tau_s)^{-1} \sum_{n=0}^{-(\tau_C/\tau_s - 1)} A(t_n) \cdot B(t_n + \tau_D) \tag{4}$$

Signals $A, B,$ etc. should be expressed relative to baseline values relatively unaffected by fire. A suitable and convenient baseline, which mitigates effects of instrument drift and normal changes in the background environment, would be the mean of a signal over an interval extending from present time into the past of a duration, τ_B, considerably longer than the correlation interval, τ_C. For example, the baseline for signal A, $\langle A_0 \rangle$, may be expressed:

$$\langle A_0 \rangle (t_0, \tau_B) = (\tau_B/\tau_s)^{-1} \sum_{n=0}^{-(\tau_B/\tau_s - 1)} A(t_n) \tag{5}$$

where it is assumed that the scan interval, τ_s, is so small compared to τ_B that it will have little effect on $\langle A_0 \rangle$.

Finally, it is possible to define nondimensional forms of the cross-correlations $\langle A \cdot B \rangle$ and $\langle A \cdot B \cdot C \rangle$, i.e. the correlation coefficients $\langle A \cdot B \rangle / (A' \cdot B')$ and $\langle A \cdot B \cdot C \rangle / (A' \cdot B' \cdot C')$, where A', B' and C' are root-mean-square values of the respective signals in the correlation interval. One might expect the correlation coefficients to remain near zero during nonfire conditions and to conveniently approach unity during fire conditions.

EXPERIMENTAL ARRANGEMENT

Some of the fire experiments were conducted in a quiescent room, others in a highly ventilated room. Fire sources were selected versions of the standard sources specified by European Standard EN54.[6] Results were analyzed on a computer with spread sheet software. Further details are given below.

Test room and instrumentation

Figure 1 shows the test room. Overall dimensions of the room were 3·66 m × 3·66 m × 2·39 m high, and it was built on the concrete floor of a laboratory underneath a large smoke hood. Walls were 13 mm gypsum board on (exterior) steel studding, and the ceiling was constructed from 0·61 m × 1·22 m × 0·013 m thick drop-in refractory panels. All seams in the ceiling were sealed with aluminum foil tape. A single, close-fitting door was installed. Observation windows were provided as well as a fluorescent light fixture on a wall against the ceiling in the room.

Ventilation, when required, was provided by a blower, N, drawing air from the return grille, D, via a plenum, I, and piping, J. An orifice meter was installed at K. The blower discharged through various

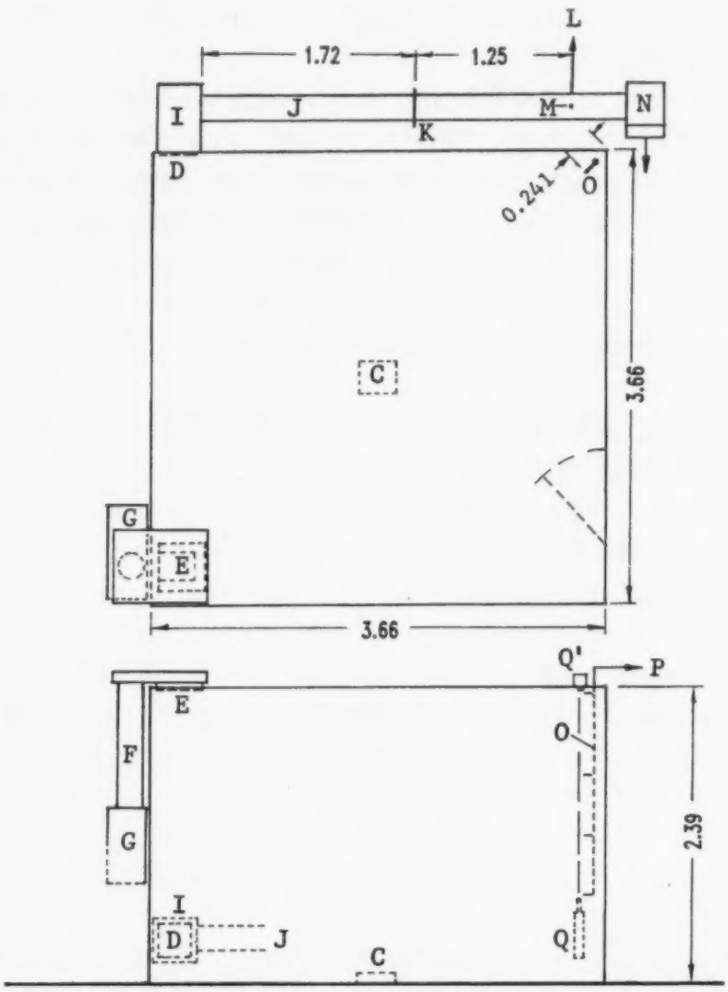


Fig. 1. Test room. Lettered components explained in text; dimensions in meters.

ducting elements into the exhaust of the smoke hood. Air flow into the room occurred at the supply grille, E, which directed the air flow into the ceiling regions. The supply grille drew air from the laboratory space via a transition piece, a vertical duct, F, and an intake box, G.

Other permanent features of the room included a weighing platform for the test fires, C, on the floor in the center of the room. In the corner diagonally opposite the supply grille was installed a vertical array of aspirated thermocouples,[7] O, with four measurement elevations, as indicated, used in tests with a quiescent room in anticipation of stratification of smoke from low-buoyancy fire sources. The four aspirated flows were merged at P for analysis by various instruments. Nearly touching the ends of the horizontal aspirating tubes was a vertical beam from a helium-neon laser, Q; the transmitted light was sensed by a photodetector, Q′, at the ceiling. The laser beam traversed within 5 mm of the aspirating ports.

During tests with a quiescent room, the air supply grille, E, and air return grille, D, were sealed.

A ventilation rate of 0·182 m^3/s was employed in all the ventilated tests, which corresponds to 20·4 air changes per hour. The aspirated thermocouples and associated sampling measurements remained passive during these tests. Instead, measurements were made in the return flow behind the measuring orifice K (Fig. 1); temperatures were monitored with a single thermocouple, M, and a sample flow for analysis was drawn at L, both approximately six pipe diameters behind the measuring orifice.

The sampled flow was analyzed for smoke densities and gaseous compounds. Smoke densities were monitored with an optical extinction/scattering meter, assembled from available components[8] and installed in a cylindrical housing. The extinction side utilized a 3-wavelength detector: 'blue' (457·9 nm); 'red' (632·8 nm); and 'infrared' (905 nm). The scattering side viewed 90° scattered light from a tungsten lamp (common light source for both sides). Smoke densities were also monitored with a standard[9] measuring ionization chamber (Danish Research Centre for Applied Electronics) mounted within a housing receiving part of the sample flow. Gaseous compounds monitored included carbon dioxide and carbon monoxide (Beckman Model 865 Infrared Analyzers) and total hydrocarbons (Beckman Model 400 Flame Ionization Analyzer). Sample transport times, between entry to the sampling system and first instrument response, were tested to be about 4 s for the smoke densities and 8 s for the gas analyzers.

Fire and smoke sources

Fire sources were selected to be equivalent to test fires specified in European Standard EN54.[6] These can be described briefly (see Ref. 6 for full descriptions):

TF1: 'open cellulosic fire' (spreading, flaming fire in an ordered pile of beechwood sticks), referred to here as *flaming wood*

TF2: 'smouldering pyrolysis fire' (beechwood sticks pyrolyzed on a hot plate powered to reach 600 °C within 11 mins), referred to here as *smoldering wood*

TF3: 'glowing smouldering fire' (lengths of cotton wick suspended vertically, smoldering upward), referred to here as *glowing cotton*

TF4: 'open plastic fire' (horizontal, square mats of flexible polyurethane foam, ignited by flame in a corner), referred to here as *flaming plastic*

TF5: 'liquid fire (*n*-heptane)' (flaming fire of *n*-heptane + 3% toluene in a 0·33 m × 0·33 m container), referred to here as *heptane*

TF6: 'liquid fire (methylated spirits)' (flaming fire of methylated spirits, with at least 90% ethyl alcohol, in a 0·435 m × 0·435 m container), referred to here as *ethanol*

Since the test room was smaller than the EN54 test room,[6] it was decided to scale the test fires down, using established scaling principles.[10] Within the tolerances allowed by EN54, the test room dimensions which best scale down to the proportions employed in the program are 9 m × 6 m × 4·16 m high. Scaled by the factor 0·575, these dimensions reduce to 5·17 m × 3·45 m × 2.39 m high, compared to the actual dimensions employed of 3·66 m × 3·66 m × 2·39 m high. Burning rates to achieve similar temperatures, smoke and gas concentrations scale as[10] the scaling factor to the power $\frac{5}{2}$, i.e. $0{\cdot}575^{5/2} = 0{\cdot}250$. Consequently, all burning areas or numbers of smoke-producing elements of a given identity were reduced by the factor $\frac{1}{4}$ from EN54 specifications.

It became clear early in the program that most of the 'reduced size' fire sources were too large to challenge the detection capability of cross-correlation techniques. In these cases, 'micro-size' fire sources were designed: whereas reduced-size TF3 employed 22 pieces of cotton wick, micro-size TF3 employed only two wicks. Further, whereas reduced-size TF5 burned 125 g heptane + 3% toluene in a 165 mm square vessel, micro-size TF5 burned 7 g of the same fuel in a 54 mm diameter vessel. Finally, whereas reduced-size TF6 burned 387 g denatured ethyl alcohol (Fisher Scientific, Springfield, New Jersey) in a 218 mm square vessel, micro-size TF6 burned 13 g of the same fuel in a 54 mm diameter vessel.

Ignitions and other source initiations were under remote control from outside the test room.

DATA ANALYSIS

The data were recorded at a rate of one scan per second using a MINC-23 Minicomputer System (Digital Equipment Corporation, Marlboro, Massachusetts, USA) and subsequently converted to engineering units.

Signal correlations were performed on a Hewlett Packard 1000 Computer System, started by reading reduced data files into spread sheet software for convenient data manipulation. The following steps were followed in establishing correlations, consistent with previous discussion.

(1) First baseline averages of the signals were developed for the baseline interval τ_B, using the current reading and the previous $\tau_B/\tau_s - 1$ readings. Often, $\tau_B = 100$ s was selected, which, together with $\tau_s = 1$ s, corresponded to $\tau_B/\tau_s - 1 = 99$ readings.
(2) Subsequently, signals for the correlations were prepared in the form of 'referenced signals', established by subtracting the current reading of a signal from its current baseline average.
(3) Correlations were established by multiplying referenced signals and averaging the current reading and $\tau_C/\tau_s - 1$ previous readings. Often, $\tau_C = 10$ s was selected which, together with $\tau_s = 1$ s, corresponded to $\tau_C/\tau_s - 1 = 9$ readings.

For the temperature data in the quiescent room, the four temperatures at the different elevations were first combined to form an average temperature, which was then treated like any signal, following steps (1)–(3) above.

For the measuring ionization chamber (MIC), the 'referenced signal' (step (2)) would normally be negative, reflecting a decrease in ionization current. It was decided to represent this signal as the negative of the operation in step (2), making the referenced signal normally positive for use in signal correlations. The output of the MIC was not converted to the ionization smoke density, y, defined in EN54[9] for the purpose of the signal correlations. However, this conversion was made later, in the analysis, using the definition:[9]

$$y = I_0/I - I/I_0 \tag{6}$$

where I_0 is the ionization current without smoke and I is the ionization current with smoke. (In practice, the MIC voltage output is used, being proportional to the ionization current.)

The optical scattering data, in the form of output voltage from the optical extinction/scattering meter, was used directly in steps (1)–(3). However, the optical extinction data at the three wavelengths and from the vertical laser beam in the room were first converted to optical densities (extinction coefficients) according to:

$$\mathrm{OD} = d^{-1} \ln (V_0/V) \tag{7}$$

where V and V_0 are the photodiode outputs with and without smoke and d is the optical path length. The optical densities at the 'blue', 'red' and 'infrared' wavelengths are represented as ODB, ODR and ODI, respectively, while that from the vertical laser beam is represented as ODV. Later, in the analysis, the extinction measurements were also interpreted in the form of optical smoke density, m, defined as in EN54:[9]

$$m(\text{dB/m}) = 10d^{-1}\log_{10}(V_0/V) \tag{8}$$

where dB/m (decibel per meter) carries the units m^{-1}. The relationship between OD and m may be verified to be:

$$m = 4{\cdot}34\,\text{OD} \tag{9}$$

RESULTS

The tests are listed in Table 1 in the order of execution, numbered BFK1 through BFK17. (The prefix BFK was adopted for the sponsor,

TABLE 1
List of Tests

Test no.	*Room ventilated?*	*Fire or smoke source*[a]
BFK1	No	Heptane (reduced-size TF5 *without* toluene)
BFK2	No	Heptane (reduced-size TF5)
BFK3	No	Heptane (micro-size TF5)
BFK4	No	Ethanol (reduced-size TF6)
BFK5	No	Ethanol (micro-size TF6)
BFK6	No	Smoldering wood (reduced-size TF2)
BFK7	No	Flaming plastic (reduced-size TF4)
BFK8	No	Glowing cotton (reduced-size TF3)
BFK9	No	Flaming wood (reduced-size TF1)
BFK10	Yes	Engine exhaust
BFK11	Yes	Arc welding fumes
BFK12	Yes	Ethanol (micro-size TF6)
BFK13	Yes	Heptane (micro-size TF5)
BFK14	Yes	Smoldering wood (reduced-size TF2)
BFK15	Yes	Smoldering wood (reduced-size TF2)
BFK16	Yes	Glowing cotton (reduced-size TF3)
BFK17	Yes	Glowing cotton (micro-size TF3)

[a] Reduced-size sources simulated standard test fires[6] in EN54 test room. Micro-size sources burned at a much smaller rate, one-tenth or less of the reduced size.

Brandforsk, The Swedish Fire Research Board.) Brief notes on the various tests are first presented, followed by examples of the data.

BFK1 was a shake-down test using heptane without toluene. BFK2 (heptane, reduced-size TF5) was considered the first valid test and gave very large signals, hardly worth analyzing by correlation techniques. BFK3 (heptane, micro-size TF5) burned at a rate only about 4% of that in BFK2, and a number of double and triple correlations were calculated for this test. BFK4 (ethanol, reduced-size TF6) was, like BFK2, also deemed too large to be of challenge to correlation techniques. BFK5 (ethanol, micro-size TF5) burned at a rate of about 3% of BFK4 and turned out to be an important challenge to correlation techniques. BFK6 (smoldering wood, reduced-size TF2) produced many good signal correlations. BFK7 (flaming plastic, reduced-size TF4) was of little challenge to correlation techniques. BFK8 (glowing cotton, reduced size TF3) generated several good signal correlations. BFK9 (flaming wood, reduced size TF1) produced strong signals and generally excellent signal correlations.

BFK10 and BFK11 were special tests to investigate discrimination against nonfire sources of smoke and fumes, which is not within the scope of the present paper. Starting with these tests, the test room was in the highly ventilated mode for the rest of the program.

BFK12 (ethanol, micro-size TF6) produced good response in terms of temperature and carbon dioxide, as had BFK5 in the quiescent room. BFK13 (heptane, micro-size TF5) generated some response in all the signals. BFK14 (smoldering wood, reduced-size TF2) revealed an intriguing anomaly; there was first a rise in the output of the measuring ionization chamber before the typical response, a decrease, began. BFK15 (smoldering wood, reduced-size TF2), a repeat of BFK14, confirmed the anomaly observed in that test. (Evidently, with the highly ventilated condition, particles driven off the wood at different stages of pyrolysis were not mixed to a great extent before reaching the sampling port, as they would have done, more significantly, in the quiescent room. Furthermore, the particles driven off early in the process appear to have had electrical properties which caused them to produce a net increase in ion flow in the measuring ionization chamber.) BFK16 (glowing cotton, reduced-size TF3) produced several good signal correlations. BFK17 (glowing cotton, micro-size TF3), the final test, had been designed to challenge the capabilities of signal correlation techniques, which this test did indeed do, although it was still judged detectable.

Altogether, 25 different cross correlations were evaluated in the program, involving the following signals: CO, CO_2, ION, ODB, ODV,

SCT, T and THC. Fourteen of these were double correlations and eleven were triple correlations. Specific correlations were selected as the program progressed, based on signal qualities in each test.

Examples of the data are presented in Fig. 2, pertaining to BFK3 (micro TF5, heptane). Figure 2(a), left, shows raw signals (concentrations) of carbon monoxide (CO), carbon dioxide (CO_2), and total

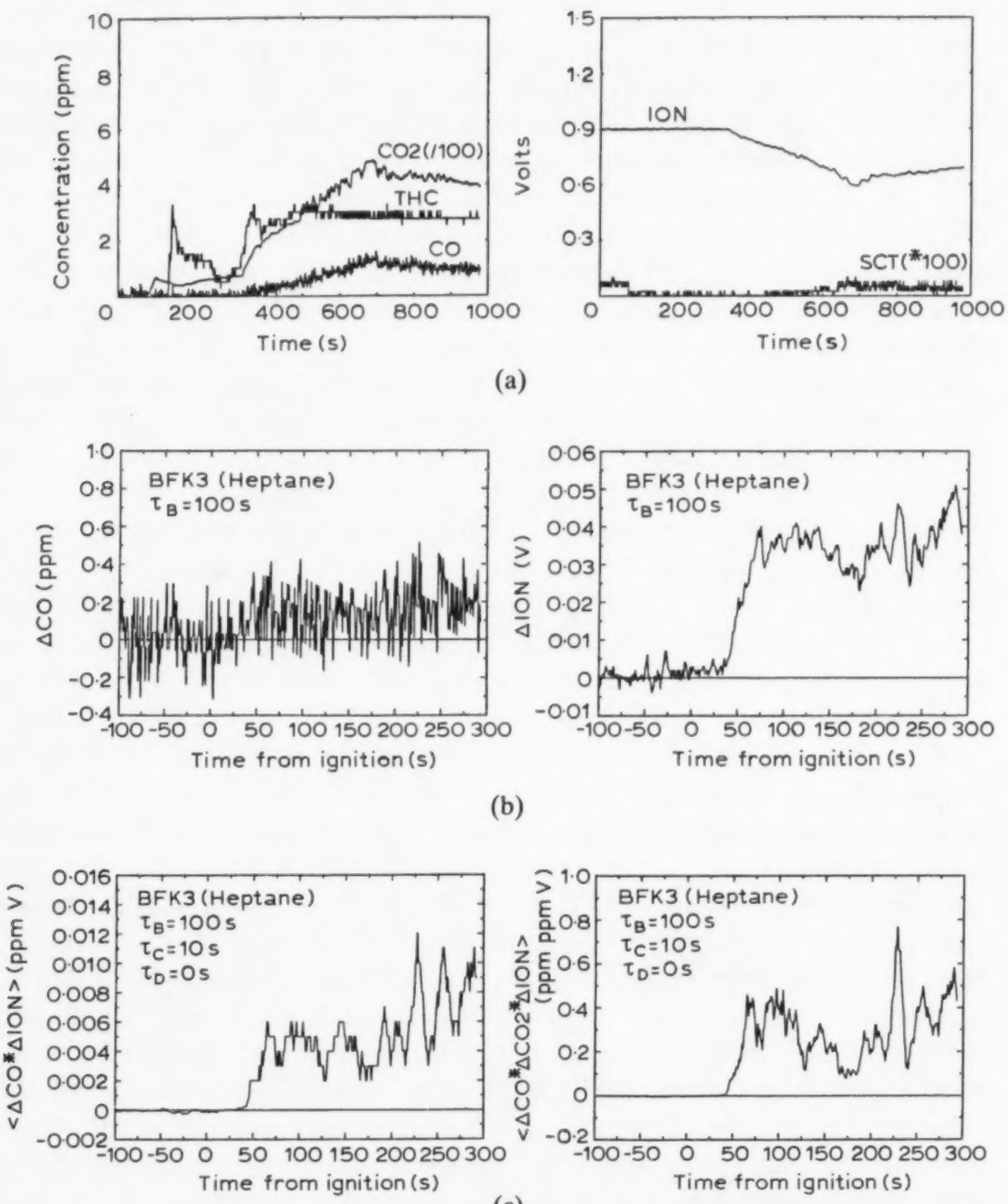
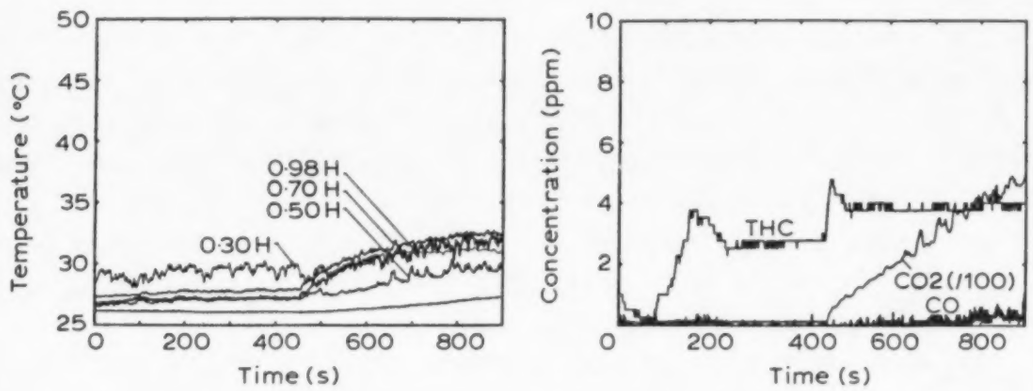
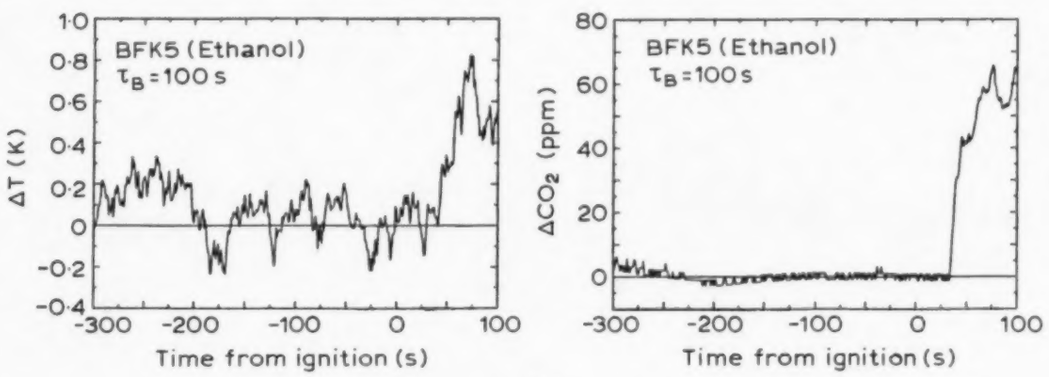


Fig. 2. Selected results for BFK3 (micro TF5, heptane). (a) Raw signals; (b) referenced signals; (c) cross-correlation.

hydrocarbon (THC). Ignition of the heptane liquid occurred at a test time of 306 s; THC concentrations observed at earlier times were caused by evaporating fuel. The figure to the right shows the output of the measuring ionization chamber (ION) and the light scattering meter (SCT). Figure 2(b) presents the referenced signals ΔCO and ΔION, obtained from the raw signals (using computer analysis of recorded



(a)



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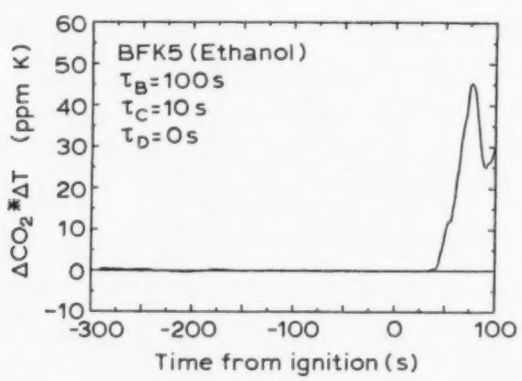


(c)

Fig. 3. Selected results for BFK5 (micro TF6, ethanol). (a) Raw signals; (b) referenced signals; (c) cross-correlation.

data) by subtracting the signal averages over the interval $\tau_B = 100$ s into the past. Figure 2(c) shows cross-correlations of referenced signals using a correlation interval $\tau_C = 10$ s, including the double correlation $\langle \Delta CO \cdot \Delta ION \rangle$ and the triple correlation $\langle \Delta CO \cdot \Delta CO_2 \cdot \Delta ION \rangle$. Both correlations do well in distinguishing fire activity from the pre-ignition ambient (very low prefire activity and wholly positive post-ignition behavior).

Figure 3 presents results for BFK5 (micro TF6, ethanol). For this clean burning source, the temperature and CO_2 signals produced the best correlation. The temperatures measured at different elevations and shown at left in Fig. 3(a) (ignition at 427 s) were first averaged, from which the referenced signal ΔT in Fig. 3(b) was calculated. The referenced CO_2 concentration in Fig. 3(b), ΔCO_2, was calculated from the raw CO_2 data in Fig. 3(a). In Fig. 3(c), the cross-correlation $\langle \Delta CO_2 \cdot \Delta T \rangle$ is seen to be of good quality.

In Fig. 4, pertaining to BFK15 (reduced-size TF2, smoldering wood, ventilated room), combined effects of increasing the baseline and

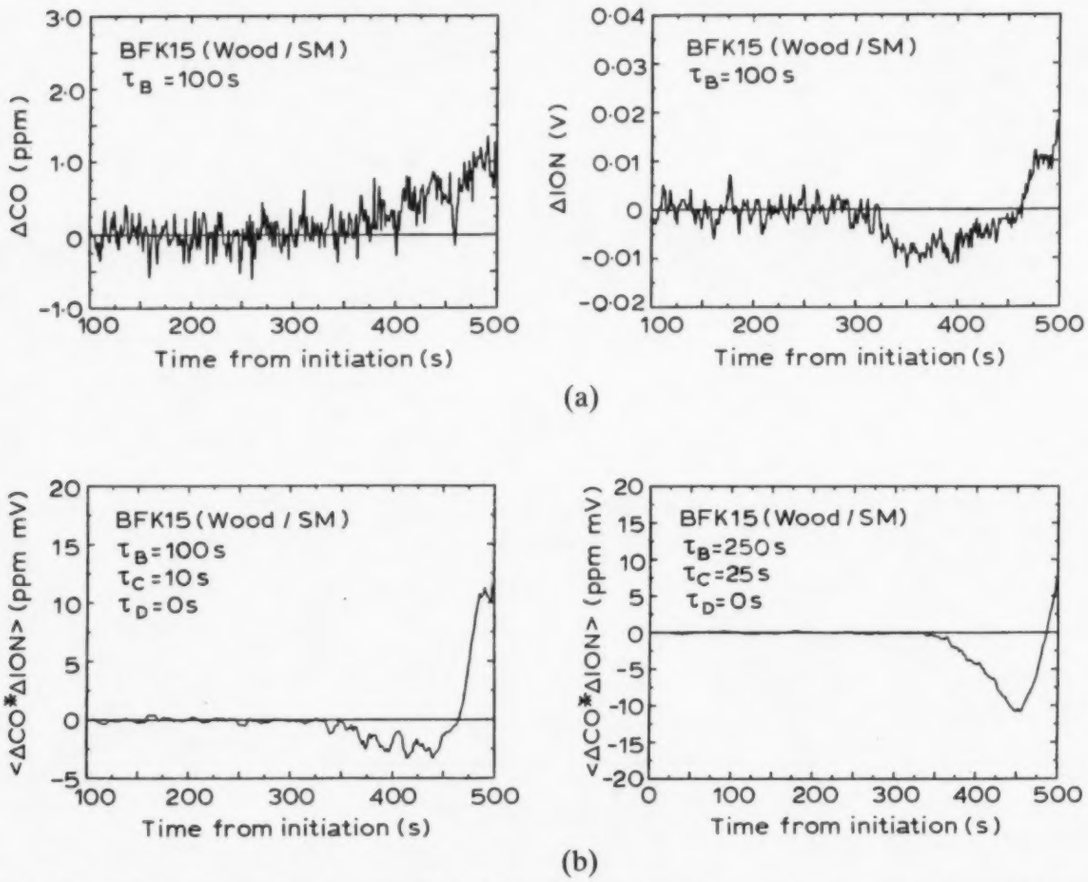
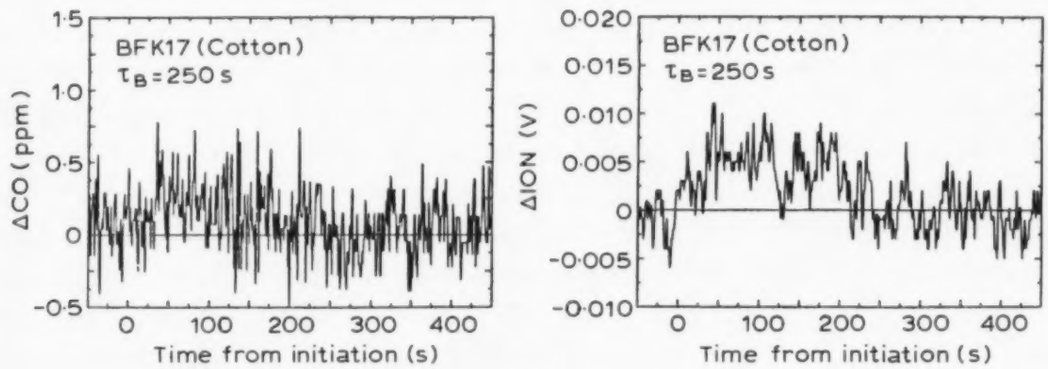


Fig. 4. Selected results for BFK15 (reduced-size TF2, smoldering wood, ventilated room). (a) Referenced signals $\tau_B = 100$ s; (b) cross-correlations for two combinations τ_B, τ_C.

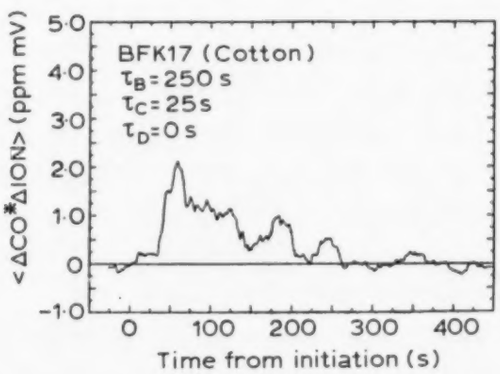
correlation time intervals can be assessed. It is recalled that this test, along with BFK14, produced an anomolous ION response. Figure 4(a) shows the referenced CO concentration and ION signal for $\tau_B = 100$ s. Figure 4(b) shows the double correlation $\langle \Delta CO \cdot \Delta ION \rangle$ for $\tau_B = 100$ s, $\tau_C = 10$ s on the left and for $\tau_B = 250$ s (requiring new referenced signals), $\tau_C = 25$ s on the right. It is clear that the longer correlation interval had a smoothing effect on the correlation, including a reduction in preignition fluctuations, and the longer baseline interval increased the magnitude of the correlation after ignition.

The most challenging fire source was micro-size TF3, glowing cotton, depicted in Fig. 5 (ventilated room). This source consisted of two glowing cotton wicks, one of which was observed to have extinguished at 140 s from 'initiation' (referring to initiation of power to heating coil which ignited wicks). Figure 5(a) presents referenced values of CO and ION, with $\tau_B = 250$ s. Figure 5(b) presents the cross-correlation $\langle \Delta CO \cdot \Delta ION \rangle$.

A few correlations were investigated in their nondimensional forms, i.e. as correlation coefficients (see Discussion of Concept). As anticip-



(a)



(b)

Fig. 5. Selected results for BFK17 (micro TF3, glowing cotton, ventilated room), (a) Referenced signals; (b) cross-correlation.

ated, the correlation coefficients soon took on values close to unity after ignition. However, prior to ignition, large positive and negative fluctuations of order unity in magnitude occurred in their values, attributed to the limited correlation interval available. Consequently, the correlation coefficient form does not appear to be practical.

DISCUSSION

In order to establish quantitatively how sensitive the present signal correlations are compared to conventional sensitivities of fire detectors, it is useful to rank them according to the sensitivity classification scheme of European Standard EN54.[6]

According to EN54,[6] detector sensitivity to the fire sources TF1–TF6 is assessed from response values of the 'fire parameters' δT (rise in gas temperature), m (optical smoke density) and y (ionization smoke density), all measured near the detector under evaluation. There are specific requirements on the wavelength range for measuring m, which is fully satisfied by the 905 nm extinction meter. Further, y is to be measured with a standard measuring ionization chamber, as used in this program. The recognized, most sensitive detector class allows response values up to $\delta T = 15\,°C$, $m = 0{\cdot}5\,dB/m$, and $y = 1{\cdot}5$ (see eqns (8) and (6) for definitions of m and y). In a three-dimensional coordinate system with axes δT, m and y, the response values associated with a detector qualifying for the most sensitive class and a given test fire must fit inside a 'box' defined by the limits quoted above. It is stated[6] that 'This classification applies only to applications for which the test conditions can be regarded as representative'. 'Test conditions' would include the test fires (TF1–TF6). It would seem that, for smoke detectors, the precise dimensions of the room and placement of detector/instrument array would be of secondary importance. Secondary effects also may be associated with installations with significant heat loss from the convective flow before it reaches the detectors/instruments, which would tend to lower the value of δT at response for smoke detectors. Other possible secondary effects may be associated with differences in smoke aging and ease of smoke entry into the detector. In the experiments of this program, the fire sources had to be scaled down, which also may have had some effect.

Despite the departures of the test conditions of this program from the EN54 conditions, it will be assumed that response values of the fire parameters can meaningfully be ranked within the sensitivity classification scheme of EN54.

In order to establish the performance of the various signal correlations within this framework, detection times and associated values of δT, m and y had to be determined. Detection times were determined once detection thresholds for the various correlations could be defined. The thresholds for a given correlation were selected as five times the maximum pre-fire value of the correlation among all the tests for which the correlation had been evaluated. Detection times and associated values of the performance parameters could then be determined.

One of the most consistently well-performing among the 25 correlations investigated was $\langle \Delta CO \cdot \Delta ION \rangle$, which responded well to all the fire sources except those in tests BFK5 and BFK12, i.e. ethanol, a clean burning fuel. A very good companion correlation to substitute for the insensitivity to ethanol was $\langle \Delta CO_2 \cdot \Delta T \rangle$. Considering these two correlations as part of a detection system, the system performance parameters (δT, m, y) could be considered to be the more favorable set of the two correlations for each fire source. In Fig. 6, these sets have been plotted on δT, m, y axes relative to a hypothetical EN54 classification box having δT, m, y limits only $\frac{1}{8}$ of those for the most sensitive EN54 class. Clearly, the detection sensitivities of the two

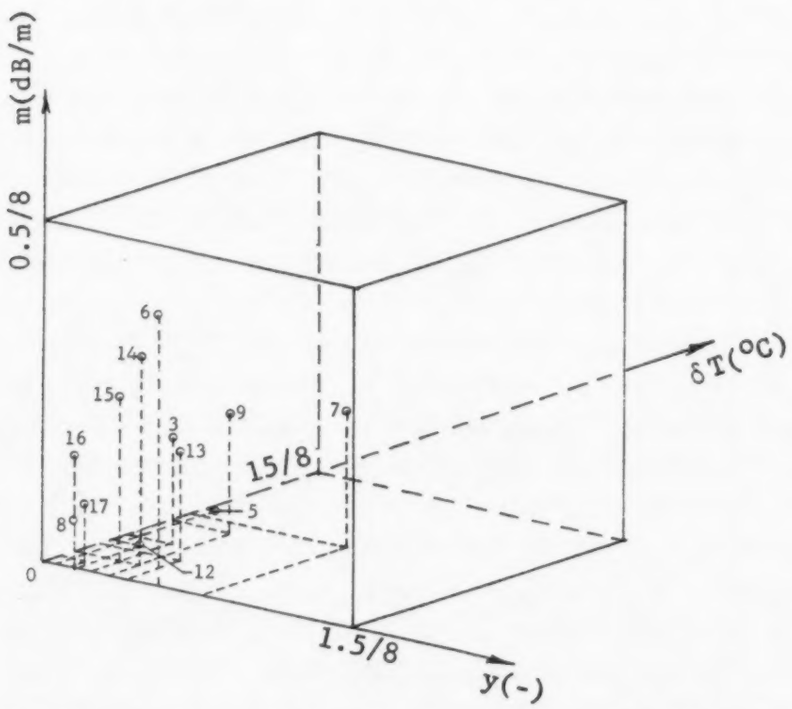


Fig. 6. Combined performance of the correlations $\langle \Delta CO \cdot \Delta ION \rangle$ and $\langle \Delta CO_2 \cdot \Delta T \rangle$ within hypothetical EN54–9 'classification box' which has δT, m, y limits equal to one-eighth of the limits for the most sensitive EN54–9 classification. Points within the box are identified with their BFK test numbers.

correlations are very high for all the fire sources, compared to the most sensitive EN54 class.

It might be of interest to note the consumptions of combustible associated with the data in Fig. 6. These ranged from 0·04 g for BFK17 to 3·9 g for BFK7.

PERSPECTIVE

This program has offered a generic study of fire detection by cross-correlation of signals from different sensors. It has demonstrated that practical, highly sensitive systems can be devised. Among the signal options available in the program, the two correlations $\langle \Delta CO \cdot \Delta ION \rangle$ and $\langle \Delta CO_2 \cdot \Delta T \rangle$ complemented each other well, the former responding to sources producing some CO together with particles, the latter backing up the former whenever the production of CO and particulates was very small, as in the case of ethanol. Baseline intervals, τ_B, were selected in the range 100–250 s, coupled with correlation intervals in the range 10–25 s, with sampling rates at 1 scan per second. The upper limits of τ_B and τ_C appeared preferable, but there was no attempt to optimize these intervals. For fire conditions developing more slowly than any of the sources included in this study, even longer intervals, τ_B, than 250 s might be preferred.

As the program progressed, it never appeared advantageous to maximize a signal correlation with respect to relative delay time, τ_D (see discussion in connection with eqns (2) and (4)). However such a procedure may be advantageous whenever fire contaminants arrive at a sampling point in bursts of short durations compared to the relative delay time of two signals.

The ION (ionization chamber) signal in this study responded to particles. Other signals responsive to particles may substitute for the ION signal, such as the signal from a VESDA® (Very Early Smoke Detection Apparatus) or a high quality extinction meter.

Optical flame detectors are now on the market which monitor the environment in two bands, an ultraviolet band and an infrared band, with a logic circuit to determine a state of alarm (the two bands exceeding assigned thresholds). Radiation fluctuations in the two monitor bands are likely to vary in phase. The sensitivity of such a detector could probably be improved substantially, using signal correlation principles, without increasing the susceptibility to false alarm.

In order to establish realistic detection thresholds for signal correlations, data are needed for extended nonfire intervals of routine activity

in the environment to be monitored. The thresholds adopted in this study were somewhat speculative since little data were available from the pre-ignition environment.

CONCLUSIONS

(1) Fire detection by cross-correlation of signals from different sensors has been shown to be a promising technique for achieving high detection sensitivity, using either double or triple correlations of signals responding to airborne products of pyrolysis or combustion.

(2) For fire sources modeled on European Standard EN54 test fires, baseline intervals, τ_B, in the range 100–250 s and correlation intervals, τ_C, in the range 10–25 s were found to be reasonable for achieving correlations of good quality, using a scan rate of one per second. Although the larger intervals gave best results, no optimization was attempted.

(3) Assuming specific detection thresholds, believed to be sufficiently high to prevent spurious alarms, two complementary cross-correlations, $\langle \Delta CO \cdot \Delta ION \rangle$ and $\langle \Delta CO_2 \cdot \Delta T \rangle$, were shown capable of detecting the complete set of fire sources (modeled on EN54 test fires) at levels of smoke density and temperature rise which are one order of magnitude lower than the limits of the most sensitive EN54 class.

(4) The correlation concept should be investigated for many additional fire sources and additional, preferably very stable sensors (including optical flame sensors), with emphasis on (a) tracking various correlations under extended nonfire intervals in different ambients, to establish realistic thresholds for detection, and (b) discriminating against nonfire sources.

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Limitations of Computer Models

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ABSTRACT

The limitations of computer models in relation to fire risk are considered in very general terms. The vital importance of the appropriate use of a model and suitable interpretation of results is stressed. Further, the possible capacity of a model to assist in the gaining of qualitative insights is considered. Some general conclusions are drawn.

INTRODUCTION

Over the last two decades there has been a great increase in the construction of computer-based models with regard to fire risk. Overall, the purpose of such models is to enable one to better assess the fire risk in a given case with particular types of occupants, contents and building design. In principle, they should help in estimating some of the likely effects of making a change to a system (whether new or existing).

During the 1970s the dominant paradigm for such models was the probabilistic one, although much deterministic work did take place. During the 1980s the probabilistic paradigm tended to be replaced by the deterministic one, although probabilistic work did continue. During the 1990s it may be the case that a synthesis of the two approaches will start to come about; the best being reaped from both paradigms. In general this would be a desirable development.

One thing can be said with certainty and that is that this whole field is changing very rapidly.

The question arises of what is an appropriate role for such models and this paper attempts to develop, in general terms, a discussion about

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the limitations of models in relation to fire risk.

A primary theme which emerges is the need to avoid the danger of seeing a model in isolation; as a *deus ex machina*. It is necessary to guard against the emergence of a 'fetishism of models' in our attitude. The complexity of the problem of comparison between theory and experiment is also explored to some degree.

TYPES OF MODELS

Broadly, there are two types of mathematical models: deterministic and probabilistic. In a probabilistic model a range of possible developments is allowed for, a probability being associated with each, e.g. the model of Ref. (1). A deterministic model predicts a single possible development. Probabilistic models are desirable to the extent that, in principle, they allow for the sheer complexity of the real world; however, the input data (transition probabilities and temporal distributions) are generally difficult to construct reliably. Deterministic models are desirable to the extent that they may help to shed light on specific processes; however, the predicted course of fire development may be at great variance with reality. In both kinds of models the assumptions made may be unrealistic. In the longer term a synthesis of deterministic and probabilistic models needs to come about, in order to gain the value of both approaches.

The remainder of this paper will refer to deterministic models as these have become very prominent in recent years. The primary types of deterministic models are zone models and field models.

QUALITATIVE AND QUANTITATIVE CONSIDERATIONS

Two aspects are important when considering a model, qualitative and quantitative. Qualitative aspects refer to conceptual assumptions and ranges of applicability. Quantitative aspects refer to how well a model predicts the values of quantitative variables in a real case.

QUALITATIVE CONSIDERATIONS

Zone models

Zone models assume the formation of a very small number of 'zones'. In particular, this type of model assumes that the smoke forms a

homogeneous layer of uniform temperature, smoke density and gas concentration. Essentially, they consider the formation of two zones; an upper 'smoke layer' and a lower layer. The assumption of distinct stratification means that zone models are only applicable to cases in which two clearly defined zones are likely to form. The exact conditions in which this is likely to be so are not well understood. However, it seems to be generally accepted that two zones have a good chance of forming if the room is of a rectangular cuboidal shape and is 'domestic-sized'. Even under these conditions it may be the case that two distinct zones do not form. For example, whether or not two distinct zones are formed may well depend upon the rate of development of the fire. Much more work needs to be done in order to identify those conditions under which a definite uniform upper layer is likely to be created. That would then help to identify those conditions under which zone models may be of some value.

Field models

Field models do not assume a very small number of zones but a variation in the 'field variables' (temperature, gas concentrations, etc.), throughout the space of concern. In practice a compartment is divided into a large number of cells (typically thousands) and uniformity of conditions is assumed within each cell. In this sense a field model may be thought of as a zone model but with thousands of zones instead of, essentially, two. In principle, therefore, values of the field variables can be predicted at a very large number of places throughout a building. Also, in principle, there is no limitation on the size or shape of building which may be modelled.

A limitation of field models is the relatively large amount of computing power and time they require by comparison with zone models.

Sub-models

Beyond the limitations of the overall conceptual assumptions of a given model there are limitations due to the assumptions in explicit or implicit sub-models; for example, assumptions in relation to heat release rate or species production.

Specific models

As examples, the qualitative features of three zone models and one field model are summarised in Tables 1, 2 and 3. The three zone models

TABLE 1
Key Design Features and Processes

	ASET	*HAZARD I*	*FIRST*	*JASMINE (Version 1·2)*
Fire growth (a) 1st Item	◐ User injects heat release	◐ User injects heat release	●	◐ User injects heat release rate
(b) 2nd Item	◐ As above	◐ As above	●	◐ User injects heat release rate
(c) Flashover	◐ If associate with given UL temperature	◐ If associate with given UL temp.	◐ If associate with given UL temp.	◐ If associate with a given temp. at ceiling
Vents	○	●	●	●
Multi-compart.	○	●	○	●
Temperature	●	●	●	●
Smoke/gas concentrations	●	●	●	●
Radiative feedback to fire	○	○	●	○
Egress (via EXITT)	○	●	○	○
Detection (via DETACT)	◐ If associate detection with a UL conc. or temp.	●	◐ If associate with given UL temp. or conc.	◐ If associate with given temp. or conc.
Fire resistance	○	◐ If associate with given wall temp.	◐ If associate with given wall temp.	◐ If associate with given wall temp.

● = Included explicitly.
○ = Not Included.
◐ = Included Implicitly (see comment).

considered are ASET,[2] FAST[3] and FIRST.[4] (FAST is part of the package HAZARD I, which also includes the subcodes EXITT and DETACT.) The field model considered is JASMINE Version 1.2.

Each of these models contains sub-models and the sub-models should be thoroughly assessed in themselves. In general, it cannot be assumed that sub-models are necessarily reliable. Beyond that, the effects on the results of the model as a whole of making different conceptual assumptions should be investigated; for example, the effects of making different conceptual assumptions in a radiation submodel.

TABLE 2
Compartment Size and Shape

	ASET	*HAZARD I*	*FIRST*	*JASMINE*
Compartment shape		Rectangular cuboid		Any
Compartment size		'Domestic-sized'		Any

TABLE 3
Key Theoretical Structure

	ASET	*HAZARD I*	*FIRST*	*JASMINE*
Assumed state	Important quasi-steady elements (gradual change from steady state to steady state)			Unsteady
Degree of resolution	Zone model (small number of zones assumed; mainly 2)			Field (thousands of zones)

QUANTITATIVE CONSIDERATIONS

General quantitative considerations

Comparison between theory and experiment
Comparison between theory and experiment is very problematic. Many issues emerge which will be touched on here briefly.

(a) Uncertainty and flexibility associated with experimental results.
(a1) Uncertainty associated with lack of controlled conditions.
Tests which are identical with respect to a specified set of conditions (e.g. regarding materials and geometry) still, in general, exhibit a variability because of uncontrolled factors such as are implicit in ambient conditions or unnoticed changes in the test facility. In general, substantial differences may be found in test results for ostensibly identical or very similar arrangements. This point is considered further in Ref. 5. This kind of variability points to the great need for replication of tests and statistical representation of results. (See also section (d).)

A dramatic illustration of the kind of difference which may result is afforded by the full-scale bedroom tests[6] conducted by the Factory Mutual Research Corporation (FMRC) in 1973/74. Test 1 produced full room involvement (FRI) at 17·5 min after ignition whilst test 2 produced FRI at 7 min after ignition. It has been speculated that the only substantial difference between the test arrangements was the humidity.

For any single isolated experiment one does not know where it would be in the spectrum of results which might be produced by a series of replicated tests.

(a2) Uncertainty and flexibility associated with experimental design
For a given test the results depend upon the experimental design, e.g. locations of thermocouples; types of instrument; sensitivity of instruments; frequency of recording. An example of this kind of variability is

given in Ref. 5 where, for a given test, two different methods produced a difference of more than 100°C in the estimated peak mean upper layer temperature.

The general point is that experimental results are not absolute but are relative to experimental design. In a given case the effect of using different experimental designs should be investigated.

(a3) Uncertainty associated with error in measurement

Experimental error may be high. For example, an error of 48% has been estimated for the measurement of heat release rate in a gas burner test.[7] In less controlled conditions the estimated error may be even higher.

(a4) Uncertainty associated with raw data processing algorithms

For a given test, with a given experimental design and a given collection of raw data resulting, there is a variability associated with the algorithms used in calculating variables which are predicted in a theoretical model. That is, for a given set of raw data, the experimental value inferred from that data for a variable of concern (e.g. upper layer temperature) depends upon how it is calculated. An example of this kind of dependence is given in Ref. 8 in which the average upper layer temperature was to be estimated from test results. Making one set of assumptions produced a curve which reached a peak in the region of 120°C but exhibited dramatic oscillations at the top over a range of 15–20°C for nearly 500 s. Using different assumptions in the processing algorithm had the effect of suppressing the oscillations to some degree. The investigators made this change because the oscillations had been regarded as 'unbelievable' and 'counter-intuitive'. This raises the interesting question of to what extent investigators arrange matters (perhaps consciously as well as unconsciously) so as to produce results which are expected. This point would apply in both experimental and theoretical studies. In a given case the effect of using different raw data processing algorithms should be investigated.

(b) Uncertainty and flexibility associated with theoretical predictions

(b1) Uncertainty associated with conceptual assumptions

Different models may contain different conceptual assumptions. For example, ASET and FIRST (both zone models) predict upper layer temperature but employ different sub-models for the flow rate in the plume.

In general, different models predict different variables and have different parameters as input. The question arises of which conceptual assumptions are plausible for a given case. The effects of different conceptual assumptions should be investigated for a model; for

example, the difference between assuming two layers and assuming uniformity (one zone) within a secondary room.

(b2) Uncertainty and flexibility associated with numerical assumptions

A given model, with a given conceptual structure, requires a given set of parameters to be assigned numbers as input. Often there will be uncertainty about the values of the parameters to be inserted.

There may also be flexibility in the input values which may be used for solution procedure parameters; for example, the chosen grid when running a field model. In general, results have been found to depend substantially on the number of grid cells and where grid cells are placed. This is in addition to the uncertainty which may be associated with input parameters related to physical and chemical properties. Variation in solution procedure parameter values may produce a significant change in predicted values.

Uncertainty and flexibility associated with input parameters means that in general there is large scope for putting in values which may be argued to be plausible and which may produce a reasonable if not good correspondence between theory and experiment. In such a case, however, the values injected may not necessarily correspond with the real world.

This indicates the very strong need for sensitivity studies to be conducted in order to gauge the effect on output of using different numerical inputs, both generally for a model and in a particular case (see also Section (d) below).

(c) Investigation of changes

Overall, studies need to be conducted to investigate the effects of changes in relation to all the issues raised in Sections (a) and (b) above; that is the effects on experimental results of changes in how and when things are done and the effects on theoretical predictions of changes in conceptual and numerical input.

(d) Deterministic chaos

A realisation of the existence of chaotic states within deterministically modelled systems has come about over the last two decades.[9,10] Such 'deterministic chaos' means that, when a system is in a chaotic state, there is hypersensitive dependence upon initial conditions and external disturbances. It implies, for example, that the behaviour of a system may depend crucially upon the value chosen for the fourth or fifth decimal place of a given input parameter (e.g. putting in a value of 1·6551 may produce quite different behaviour to putting in 1·6552).

This kind of effect results from the non-linearity of the system. The existence of extreme sensitivity in chaotic regions has profound

implications for science in general and comparison between theory and experiment in particular. The question arises: 'Do chaotic regions exist within models of concern and, if so, where?' (Certainly there is good prima-facie reason to assume that chaotic states exist within systems associated with fire. The Navier–Stokes equations of fluid flow are non-linear and radiation terms are very non-linear.)

It also means that in chaotic regions two theoretical predictions of different behaviour corresponding to two very close input points cannot be tested experimentally as the input points would be too close to be differentiated in an experiment.

Further, it raises fundamental questions about the limits in principle to repeatability of an experiment.

The implications of deterministic chaos for prediction using fire models requires extensive and deep study.

(e) The term 'validation'

Use of the word 'validation' has become common and this is unfortunate because it is misleading. To say that a model has been 'validated' implies that it has been 'proven correct'. However, the concept of 'proving' a model to be 'correct' is directly contrary to scientific method. It is logically impossible for a scientific theory in general and a model in particular to be 'proven correct'. The most that can be done is to compare theoretical prediction with experiment and observe the differences. There is no number of 'good comparisons' which may be taken to have proved a model to be 'true'; comparison between theory and experiment needs to go on continually.

Use of the word 'validation' should be discontinued. If a person wishes to refer to comparison between theory and experiment then that is the phrase which should be used.

(f) The need for reliable data sets

There is a need for reliable sets of data for different cases. Each set would consist of a replicated series of tests in order to give some idea of the variability implicit in fairly well-controlled conditions. Also, many of the variables for which some models (such as field models) are capable of predicting values are not measured in experiments. There need to be developments in experimental techniques in order to remedy this in order to try to ensure that all of a model's output is capable of being compared with experimental results.[11]

(g) Independence of assessment

All the above considerations strongly suggest that assessment of models should be carried out by people who are as independent as possible.

That is, by people who do not have a direct interest in trying to show that a particular model is necessarily 'good' or, conversely, 'bad'.

Use of a model

(a) Single run of a model

Given all the above it may be said that in general a comparison of a single run of a computer model with the results of a single experimental test is of very limited value. Further, a good correspondence between theory and experiment in such a case does not necessarily mean that the model is a good one.

(b) Sensitivity considerations

When applying a model to a particular case it is in general necessary to consider the effects of altering input parameters. In this way a series of runs is desirable, showing the sensitivities of the model in that case.

(c) Limitations and interpretation

It is important that the user be aware of the specific limitations of the model under consideration in both qualitative and quantitative terms. Interpretation of the numbers resulting from a model must not be done in a simplistic, automatic, manner. The results from a model need to be seen in the light of the characteristics of the model.

The importance of suitable interpretation of the results from a model cannot be stressed enough.

(d) Supporting role

Having carried out sensitivity considerations for a model in a particular case the results should be seen in the light of other fire knowledge and experience in an effort to enhance understanding in the case of concern. The results of the simulations may be used as a spur to thinking and consideration of the problem. If the results of computer simulations seem contrary to other knowledge or experience then it may be that the results of the model are wrong. It may, however, mean that the model has elucidated an effect which is genuine but which is not immediately apparent. Either way, what a model seems to be suggesting should be considered in the light of the user's other knowledge and through this interactive process either be rejected as unrealistic or not.

The additional point may be made that if the only alternative to the use of a model is the direct use of 'engineering judgement' or 'guesswork' then the appropriate use of a model may be valuable. This is a valid point. However, inappropriate use of a model may result in a more hazardous situation than if 'engineering judgement' alone were used. The general principle remains that the results of a model must be

interpreted in the light of other knowledge and experience. Simplistic use of a model is dangerous.

(e) Qualitative insights
At the present time at least it seems likely that fire models may be more valuable as spurs to stimulate the development of qualitative insights rather than being assumed to be quantitatively accurate. In this way a model may help to make explicit some of the processes which are implicit.

(f) Use in comparative studies
In the spirit of the foregoing considerations it might be said that at the present time models may be of value in helping to stimulate awareness of the likely effects of changes to a building and/or its contents. That is, they may perhaps be usefully employed in a comparative sense rather than being interpreted in a sense of quantitative exactitude.

Specific quantitative considerations

Overall comments
(a) Complexity of the issues
Overall it cannot be assumed that any given model is unequivocally 'good' or 'bad'. The issues involved become complex and intertwined as indicated earlier.

(b) Sensitivity studies
For any given model comprehensive and exhaustive sensitivity studies need to be conducted.

(c) Comparisons between theory and experiment
Overall, far more comparisons between theory and experiment need to be conducted. Such comparisons should be carried out by people who are independent, i.e. who have not had a direct involvement in the development of the model and who do not have a particular interest in seeing a model presented as either 'good' or 'bad'.

(d) Lack of consistency of predictions
Overall it should not be assumed that any specific model gives results which are consistently higher or lower than experimentally observed values for any particular variable such as temperature. Further, it cannot generally be assumed that the results from one model will be consistently higher or lower than results from a different model for a given variable of concern; when applied to a particular case.

Specific comments

(a) Temperature prediction

(a1) Zone models

Zone models assume the formation of a homogeneous upper layer, i.e. the smoke layer. They further assume that the upper layer has a uniform temperature throughout its volume. That is, they do not predict the temperature at a particular place or in a particular small region.

The temperature predicted, therefore, is not the temperature near the ceiling but the upper layer temperature, which would be expected to be less than the temperature near the ceiling. As a fire develops the smoke layer is assumed to gradually become thicker and as that happens the calculated upper layer temperature would be expected to move further away from the near-ceiling temperature, in principle.

Because zone models predict upper layer temperature but in an experiment thermocouples are used to measure temperature at a point, zone model predictions cannot be directly compared with experimental results. Further, deducing an average temperature from experimental readings may be done in many different ways and produce many different experimental averages. Given the above, it is generally difficult to see whether a zone model is overpredicting or underpredicting temperature, by direct comparison with thermocouple readings.

Further, it cannot generally be said that any single zone model may be assumed to predict higher or lower values than any other zone model.

It is also important to bear in mind that a great variability in the time from ignition to maximum temperature is often observed in ostensibly identical experimental tests. (Although the actual maxima reached may perhaps show less variability. Much more work needs to be done on replication to identify and elucidate such characteristics.) Because of this the predicted time from ignition to maximum temperature may be greatly different from that found in a single experimental test. This also applies to field models.

(a2) Field models

Unlike the zone models, field models are capable of predicting the temperature at the centre of each of a large number of cells throughout a building; typically at thousands of points. If the grid is specified to have a thermocouple position at a cell centre then the model will predict the temperature at that position. This means that temperature predictions from field models can be compared directly with experimental measurements.

(b) Prediction of smoke obscuration

At the present time very considerable uncertainties are associated with the prediction of smoke obscuration. The modelling of solid particle/liquid droplet production has a long way to go before it can be regarded as reliable. Beyond that, the scattering and absorption of light is very problematic as well. Zone models generally assume a multiplicative factor or 'yield' to be applied to the mass consumed by fire. Such a yield has been found to vary considerably depending upon fire conditions.

For example, the smoke obscuration yield for polyurethane foam has been found to increase by a factor of 2 or 3 depending upon conditions and even more for wood.[12] Also the actual yield would probably change throughout the duration of a fire. As with temperature prediction, zone models assume uniformity throughout the upper layer when computing smoke obscuration. This means that they cannot be directly compared with experimental results.

Overall, prediction of smoke obscuration by zone models must be regarded with very great circumspection. Such predictions may, perhaps, be useful heuristically and/or in a comparative sense. That is, differences predicted using different inputs for a given case or predicted differences between two different cases may serve a function as spurs to thinking.

Smoke obscuration predictions by field models can be more directly compared with experimental measurements as predictions refer to given points and measurements refer to given detector positions.

However, it may be that the method of calculating smoke obscuration is to assume a correlation with the gaseous product of combustion concentrations. Calculated results may then show the predicted smoke obscuration to be considerably different to measured values. The smoke sub-model cannot necessarily be assumed to be accurate in a field model. It needs to be investigated in any given case.

(c) Prediction of carbon monoxide concentration

Prediction of carbon monoxide concentrations may be generally regarded as even more uncertain than smoke obscuration predictions at the present time.

As with smoke obscuration predictions, for the zone models a 'yield' is assumed corresponding to the amount of CO produced per unit mass consumed by the fire. However, experimental estimates of CO yield have been found to vary enormously for a given fuel type depending upon the test conditions and precise fuel composition. For example, estimates of the carbon monoxide yield for polyurethane have been

found to vary by more than a factor of 80. Amongst other things, results have been found to depend upon the intensity of the heat flux incident on the fuel and the ventilation conditions. Large differences have also been found between results from large-scale and small-scale tests.[13–16]

Given this, predictions of carbon monoxide concentrations by zone models should, at the present time, be regarded as no more than broadly indicative in an extreme sense of the phrase. They may, perhaps, be of some very limited value if used in a comparative manner, as an aid to thinking.

Also, it cannot necessarily be assumed that predictions of CO levels by field models are accurate. That is, at the present time, it cannot be assumed that a field model will necessarily give better predictions of CO concentrations than a zone model. However, the incorporation of sub-models, such as the laminar flamelet model into JASMINE, will, it is hoped, improve the accuracy of CO predictions.

LACK OF OPENNESS OF COMPUTER CODES

Some computer source codes are not available for inspection or are available for inspection by a restricted number of users upon payment of relatively large amounts of money. For example, the source code for the field model FLOW-3D,[18] which has been produced at the Harwell Laboratory, is only available to the purchasers of the package upon payment of a substantial extra sum of money; and then only under restrictive conditions. Also JASMINE uses the CFD (Computational Fluid Dynamics) package PHOENICS to solve the differential equations of concern. However PHOENICS is owned by the software company CHAM Ltd, and hitherto the source code has not been made available to the public for commercial reasons. That is, the object (i.e. compiled) code only is available to a user. Also a period of about a year elapsed after the launch of the commercial version of FAST before the source code was made available to the public.

This means that some codes are therefore not open to scrutiny by the public, in general and the scientific community in particular. This is a wholly unacceptable state of affairs for two main reasons:

Scientific unacceptability

It breaches a fundamental principle of science, i.e. that a scientific hypothesis or model should be open to scrutiny by the public in general

and the scientific community in particular. It may be argued by the devisers of a code that if the basic theory is made open then the details of solution are immaterial and may be kept secret. This is not a tenable argument, however, because:

—A code may not actually do what the devisers of the code think it does; either in relation to the calculational detail or in relation to the intended response to given physical circumstances.[21]

—There may be mistakes in the code which the devisers are not aware of and which may only emerge during use or examination by others.

—The code may not actually do what the devisers claim it does. This is a different point to the first point made above.

—The details of the solution procedure do affect the result and ignorance of the details by a user may lead to mis-interpretation of results.

—Full details of the basic theoretical assumptions may not be made clear and explicit.

More generally, the whole subject area of 'software reliability' has been emerging over the last few years around issues of this kind, especially in the field of artificial intelligence[19,20] and safety critical systems.[21,22]

Beyond that there is the different but related issue of the seemingly increasing lack of reliability of the design of microprocessors due to their sheer complexity.[23] The view has even been expressed that during the 1990s people will be 'killed or injured as a pretty direct effect of either mistakes in complex software or mistakes in the design of micro chips'.[24] The extent to which this view is justified or not is a matter of discussion.

Public safety

Public safety may be compromised unnecessarily if computer codes are involved in decision-making and those codes have not been open to continuing scrutiny by the public in general and the scientific community in particular.

MODELS AND QUALITATIVE INSIGHT: EXAMPLES

Some specific examples of theoretical models helping to stimulate qualitative insights have come to light. Three of these relate to the field model JASMINE and one to the zone model HARVARD 5, the precursor of FIRST.

JASMINE

The trench effect

The 'trench effect' has become associated with the King's Cross Underground fire of November 1987. The tendency for flames to adhere to the surface of an inclined slope, when the fire is across the entire width of the surface itself, is something which emerged from running JASMINE[17] and had also been seen in results of the field model FLOW-3D. Subsequent experimental work has shown the trench effect to exist in test conditions.

Battersea Power Station

Work conducted, using JASMINE, on the proposed conversion of Battersea Power Station to a leisure complex showed that for the initial design of ventilation system being considered the smoke concentrations near floor level would be expected to be very high for the fires considered. That is, it showed that the plume was 'forced over' onto the ground. This qualitative insight led to a change in the design of the proposed ventilation system.[25]

Low temperature 'islands'

Work conducted on JASMINE 1·2 has suggested that 'islands' of relatively low temperature may be formed near ceiling level when the fire source area has a large aspect ratio of length to width (such as a counter in a department store). Whether or not this is to be confirmed experimentally remains to be seen. If this effect is found to exist in the real world then it would indicate places where it would be unwise to place sprinkler or detector heads.

HARVARD 5

Several years ago the issue arose of to what extent the smoke layer depth in a room depends upon the height of an open door relative to ceiling height.[26] In particular, the question was asked: for a typical domestic room with a fire in it and an open door, would the smoke layer depth be very much less if the door height were the same as the ceiling height (i.e. zero transom depth) than if there were a relatively small transom depth? If so then it might make sense for the section of wall above a door to be automatically raised in the event of fire, to allow smoke to escape.

Prime facie it might seem that it would be the case that for zero transom depth then the smoke layer formed in the room would be significantly less deep than otherwise.

Computer runs using HARVARD 5 were made for these cases for a room 2·4 by 3·7 by 2·4 m high. The computer simulations suggested that the existence of a section of wall above the door made little difference to the depth of the smoke layer in the room. That is, the model was suggesting that to have a raisable flap above a door would not be expected to make very much difference to the layer depth in the room. Further, it has been argued that subsequent experimental work has tended to bear out this conclusion.

(There would, of course, be limits to the validity of this conclusion. A large transom depth would be expected to affect layer depth.)

Overall, the model was suggesting that the effect of different transom depths is less than might be thought prima facie; and it has been argued that this has tended to be supported by experiment.

CLOSING COMMENT

At the present time at least the issue is not so much whether a model is necessarily good or bad in absolute terms but rather whether or not a model has the potential to assist in the process of gaining a better understanding in a given case.

If a given model does have a potential in this way then whether or not it is valuable or misleading depends upon the case to which it is applied and how results are used and interpreted. It is dangerous to see a model in isolation; examination of the context of use is as important as examination of the model itself.

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Calendar

1992

17th International Conference on Fire Safety
13–17 January 1992, Millbrae, California, USA

Organized by the Product Safety Corp.
For details contact: Dr Carlos J. Hilado, Product Safety Corp, PO Box 2328, Sunnyvale, CA 94087, USA. Tel: 1 408 732 5325.

Cables and Fire Protection (conference and exhibition)
16 January 1992, Heathrow, London, UK

Organized by ERA Technology
For details contact: Angela Barkes, ERA Technology Ltd, Cleeve Road, Leatherhead, Surrey KT22 7SA, UK. Tel: 44 372 374151, extn 2313; Fax 44 372 374496; Tx: 264045.

Fire Safety Management (course)
19–24 January 1992, Grantham, UK

Organized by the Fire Protection Association
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Flame Retardants '92
22–23 January 1992, London, UK

Organized by the Plastics and Rubber Institute and other bodies.
For details contact: Plastics and Rubber Institute, 11 Hobart Place, London SW1W OHL, UK. Tel: 071 245 9555; Fax: 071 823 1379; Tx: 915719 PRIUK G.

International Fire & Security Exhibition and Conference (IFSEC '92)
30 March–3 April 1992, Olympia, London, UK

Organized by Blenheim IFSEC
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UTECH '92 (polyurethanes conference)
31 March–2 April 1992, The Hague, The Netherlands

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27–29 October 1992, London UK

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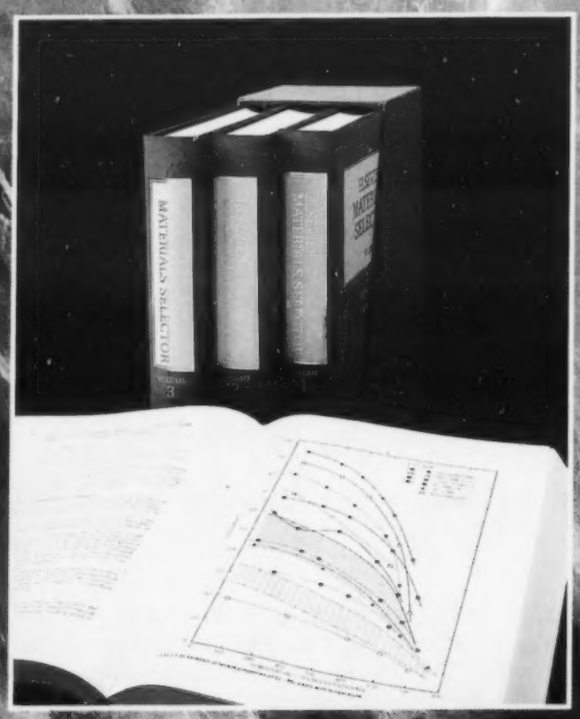

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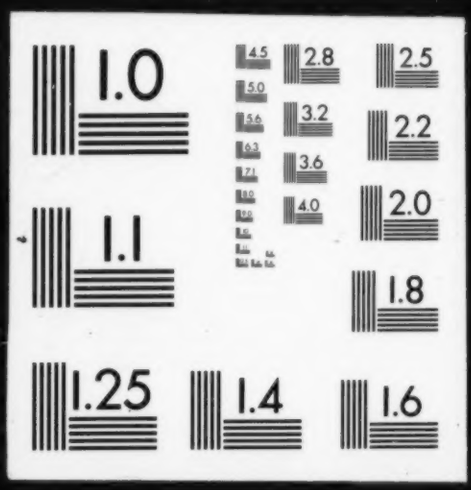
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